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Evaluation of Innovative Vessel Inspection Techniques (Phase II, Advanced Technology)

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16. Abstract
This report provides the results of the effort to evaluate marine inspection equipment and techniques for use by Coast Guard marine inspectors. Previous reports identified many potentially useful techniques that could enhance inspections both by providing better information and by speeding up inspections. Some of the equipment required, primarily lighting equipment, was previously investigated and reported on. More advanced techniques, including some under development and not commercially available, are the subject of this report.

The technology categories covered include: remotely controlled lights, video systems, climbing inspectors, fiber-optic video scopes, robotic manipulators, robotic climbers and walkers, acoustic and microwave imaging, thermography, and polarized light techniques. Candidate equipment were identified, where available, based on manufacturers literature in each category. These were ranked based on criteria selected by the contractor as important in the inspection process. The Coast Guard chose equipment based on this ranking and arranged for field demonstration of the equipment.

Equipment was demonstrated on board a ship at the Philadelphia Navy Yard and at shore sites. The observations of the government and contractor personnel witnessing the demonstrations are summarized in this report. Some of the remote video systems and use of climbing inspectors were found to be promising techniques for use in marine inspection, and with some refinements could provide safer and more efficient inspections.

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METRIC CONVERSION FACTORS

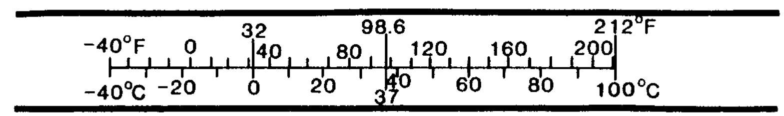
Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (WEIGHT)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (EXACT)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in = 2.54 (exactly).

Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (WEIGHT)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	0.125	cups	c
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (EXACT)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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1 INTRODUCTION

1.1 Background

1.1.1 Phases of the Study

This report documents the results of the third phase of a continuing program to identify and evaluate equipment to improve the efficiency and effectiveness of structural inspections of large steel-hulled vessels. Throughout the study, emphasis has been placed on equipment and techniques to improve the initial screening phase of inspections and surveys. During this phase the inspectors or surveyors gain an overall impression of the space being inspected and identify potential problem areas which require closer inspection. The three phases of the study are listed below.

Phase 1 - Innovative Inspection Techniques

The first phase entitled "Innovative Inspection Techniques," (Goodwin and McClave, 1993) identified technologies which might be useful to Coast Guard inspectors, classification society surveyors, independent hull surveyors, or nondestructive test personnel. No equipment was acquired or tested during the first phase of the program. The scope of equipment and techniques encompassed the following areas:

- Visual inspection equipment, including portable and fixed lighting equipment, magnification devices, fixed and hand-held video equipment, night vision, fiber optics, and polarization enhancement techniques.
- Physical access enhancements, including rafting, staging, and built-in access provision.
- Close-up testing and non-destructive testing equipment, including dye penetrant, ultrasonics, magnetic particle, eddy current, acoustic emission, and a number of other NDT techniques.

Phase 2 - Evaluation of Innovative Inspection Techniques

The second phase of the program, entitled "Evaluation of Innovative Inspection Techniques" (Goodwin and McClave, 1994), focused on equipment identified during the first phase which could be used by Coast Guard inspectors themselves. A number of specific items of hand-portable equipment were identified, ranked and prioritized. Promising items of equipment were purchased and tested in the field under actual inspection conditions. This equipment included hand-held lighting equipment (both flashlights and larger hand-carried lanterns), magnification devices, hand-held video cameras, and night-vision equipment.

Phase 3 - Advanced Inspection Techniques

The purpose of this final phase of the program is to identify, rank, and field-test complex equipment and technologies identified as potentially useful in Phase 1 but not evaluated in Phase 2. Many of these were identified in Allen, 1993. The main emphasis was still on equipment that can be useful in the initial screening stage of an inspection or survey.

A majority of the equipment studied in this phase is more likely to be used by classification society and independent surveyors or by NDT contractors working for shipyards or vessel owners than by Coast Guard inspectors. However, the results of surveys performed by non-Coast Guard personnel with this equipment are often used by Coast Guard inspectors to plan their inspections. Therefore, the Coast Guard needs to evaluate the reliability of the information obtained with this equipment. In each of the various categories, equipment which is commercially available, or at least which can be demonstrated in an actual or simulated vessel inspection environment was ranked by expected effectiveness and by benefit/cost ratio. Test plans were developed to allow comparative evaluation of various items of equipment in each category. Demonstrations of selected equipment were carried out on board a Navy replenishment tanker and in the Coast Guard Research and Development Center laboratories. A visit was also made to ROV Technologies factory to view their crawler type and pole-mounted inspection systems.

1.1.2 The Coast Guard Marine Inspection Process

A typical Coast Guard inspection of a U.S. flag deep-draft vessel occurs when the vessel is in a shipyard for regularly scheduled repairs and maintenance. Before the shipyard period, the vessel is surveyed for its owners by an independent surveyor or by the owner's own surveyor to determine its structural condition and to enable advance planning of the work to be performed in the yard. A classification society survey may coincide with the owner's survey.

Vessel owners generally provide information from their survey to the Coast Guard inspectors before the Coast Guard inspection begins. The Coast Guard inspectors use this information to plan their inspection. They closely inspect all problem areas which they have been made aware of, evaluate the proposed repairs, and inspect the repairs after they are completed. They also conduct an overall screening inspection of the entire vessel to assure themselves that the owner has not missed or failed to report any deficiencies. A previous task, "Evaluation of Innovative Inspection Techniques," reviewed equipment to improve the effectiveness of the Coast Guard inspectors during this screening phase of the inspection.

In the future, it is likely that the Coast Guard will rely increasingly on information which is provided by the owners and their surveyors and by classification society surveyors about a vessel's structural condition. Vessel owners, independent surveyors, and classification society surveyors are presently experimenting with new equipment and technologies to

improve the effectiveness and efficiency of their own surveys. The Coast Guard has a twofold reason for independently evaluating the effectiveness of these technologies:

- The Coast Guard needs to ensure the reliability of information about a vessel's structural condition which is obtained with the use of new technologies and equipment and which is provided to them at the start of an inspection.

- It is in the Coast Guard's interest that effective new technologies for vessel inspection be identified, tested, and brought to the attention of vessel owners, independent surveyors, and classification societies.

1.1.3 Remote Inspection of Tankship Structure

The cargo block of a tank vessel typically consists of six rows of tanks with three tanks across each row, separated by oil-tight bulkheads, for a total of 18 tanks. The centerline tank in each row is generally larger than the wing tanks. Internal supporting structure is located in the wing tanks to the extent possible. The centerline tanks have supporting structure on at least one transverse bulkhead, on the overhead, and usually on the tank bottom. If the tanker has a double bottom then the bottom structure is located in the double bottom. Newer tankers are being built with double sides. In these designs, much of the wing tank structure is moved to the double side voids. Thus, tankers have some tanks with little or no structure and some tanks or voids with a great deal of structural stiffening present.

The cargo tanks of conventional tank vessels are accessible only from the main deck and through two types of openings, access trunks and tank cleaning openings. Access trunks (ullage openings) are large round or elliptical hatches on raised trunks. There is usually one access trunk per cargo tank, with a deck opening, usually elliptical, about 18 x 24 inches. Access trunks are almost always located against a bulkhead (or against a web frame in a wing tank). A sloping ladder, which is approximately the full width of the deck opening, and which has handrails, leads down from the opening and generally terminates at a landing 15 to 30 feet below the deck, from which another ladder or series of ladders proceeds to the bottom of the space. Because of physical obstruction caused by the ladder and the landing directly below the opening, and because of the visual obstruction caused by the adjacent bulkhead or web frame, the ullage opening is a poor insertion point for remote imaging equipment.

The tank cleaning openings (usually called "Butterworth" openings for a company which manufactures tank cleaning equipment) are round holes with simple bolted access plates on the main deck, with clear openings from 12" to 15" in diameter. There are typically 4 or 5 openings per tank, spaced approximately 50' apart. The tank cleaning openings are intentionally not located next to bulkheads or web frames and they are placed strategically to provide direct cleaning access to as much of the internal bulkhead surface and internal structure as possible. For this reason the tank cleaning openings are ideally suited as insertion

points for visual imaging systems. However, they are relatively few, quite far apart, and small in diameter.

1.1.4 Hazardous Locations on Tank Vessels

On tankships, the cargo tanks, the pump-rooms, and the main deck are the most common locations where equipment approved for hazardous locations may be required. If all cargo tanks are not either inerted or certified safe for hot work, the main deck of the vessel, where the cargo tank vents are located, is considered a hazardous location and all electrical equipment used there must be approved. In the shipyard situation in which most Coast Guard inspections are conducted, tanks are usually certified as safe for hot work, and therefore approved equipment is not required anywhere except possibly in the cargo pump rooms.

1.1.5 Equipment Approved for Use in Hazardous Locations

Electrical equipment which is used in spaces which could have explosive atmospheres and which have not been tested and cleared by a certified gas chemist as "safe for hot work" must be approved for use in hazardous locations. There are three basic categories of approved electrical equipment, "intrinsically safe", "explosion-proof", and "purged". Approvals for intrinsically safe and explosion-proof equipment are granted after design review and testing by various private and governmental agencies. All approved equipment is conspicuously marked with the type of approval and the name of the certifying agency.

Equipment which is "intrinsically safe" is not capable of generating a spark of sufficient energy to ignite an explosive atmosphere. Approvals are granted by Underwriters Laboratories, Factory Mutual Laboratories, the Canadian Standards Association, or the U.S. Mine Safety and Health Administration. These approvals are generally limited to battery-powered portable lights, hand-held radio transceivers, certain electronic equipment, and other small equipment operating at DC voltages under 12 V. Equipment which has electric motors or which uses higher voltages usually cannot be granted this type of approval.

The second category of approved equipment is "explosion-proof". Explosion-proof approval is granted by Underwriters' Laboratories. Explosion proof equipment may operate on high AC or DC voltages. This equipment <u>can</u> generate enough energy to ignite an explosive atmosphere, but it is sealed to prevent explosive gases from reaching the source of ignition. Additionally, it must be strong enough to contain an internal explosion should explosive gases penetrate the seals and it must be able to cool and vent the combustion gases from such an internal explosion to the outside explosive atmosphere without causing ignition of that explosive atmosphere. It must also have sufficient thermal mass that the heat generated by an internal explosion does not cause its outside case to reach temperatures high enough to ignite an outside explosive atmosphere. Explosion-proof equipment is, by necessity, large, strong, and heavy.

All electrical connections for power or signal transmission to explosion-proof equipment must also be explosion-proof in order for a system to retain its approval. This is routinely done with hard-wired equipment through the use of explosion-proof conduit and fittings, however, it becomes very difficult when flexible cables are used.

Explosion-proof enclosures are available for equipment such as video cameras and lights which are not themselves explosion-proof or intrinsically safe. These enclosures generally resemble sections of heavy-wall pipe with windows in one end, and are large and heavy. All electrical connections and cables which connect with explosion-proof equipment must themselves be explosion-proof or intrinsically safe.

ISO Standard S12.4-1970 provides for a third method of making electrical equipment safe for use in hazardous locations. In this technique, called "X purging", all equipment is sealed gas-tight and provided with closed-loop air or inert-gas purging to prevent hazardous atmospheres from collecting inside the equipment. Any flexible cables which are part of the system are included in the purging loop. Clean air or inert gas is circulated throughout the system, displacing any leakage of flammable gas, which is then exhausted into a safe location. This technique allows AC powered or motor-driven equipment to be rendered safe for hazardous locations without the excessive weight and bulk of explosion-proof enclosures, and provides a reasonable way of dealing with the problem of flexible power and signal cables.

1.2 Scope

This study focused primarily on commercially available equipment which could be demonstrated and evaluated in an actual inspection environment. The emphasis was on portable equipment which could be brought aboard a vessel (or to a dockside site), set up, and moved without cranes or other mechanical lifting equipment.

A number of developmental technologies are described briefly. These were selected from devices which could be demonstrated in a controlled laboratory setting and which might eventually lead to the development of portable devices. In several cases, the components necessary to assemble a system are commercially available, but no single integrated system is commercially available.

2 TECHNOLOGY IDENTIFICATION AND PRIORITIZATION SUMMARY

2.1 Inspection Categories

The following categories of equipment were included within the scope of this study:

- Remotely Controlled Lights
- Video Cameras/Video Camera systems
- Visual Inspection Techniques
  - Climbing Inspectors
  - Fiber-Optic Video-Scopes
- Flat Plate Inspection Techniques
  - Robotic Arms and Manipulators
  - Climbers and Walkers
- Imaging Systems
  - Acoustic Imaging
  - Microwave Imaging
- Non-Destructive Techniques
  - Thermography
  - Elevated-Temperature Laser Ultrasonics
  - Polarized Light
  - Laser Weld Scanner
  - Modal Analysis

2.2 Performance and Cost Rating Factors

A large number of manufacturers were contacted for information about equipment in each category. After reviewing the literature supplied by the USCG, equipment clearly not suitable for the inspection requirements based on function and performance were dropped from further consideration. The primary criterion was the ability of the equipment to enhance the initial screening stages of tankship inspection. No equipment was excluded as result of price alone.

Important characteristics of each category of equipment were identified, and a specification chart was prepared in matrix format for each category, including all devices which showed promise. A performance rating and a cost rating system were also defined for each category of equipment. Performance ratings and performance/cost ratios are reported for each device.

For each class of device, a separate performance and cost-benefit rating system has been devised to rank the significant desirable and undesirable characteristics of that type of device. The factors are different for each type of device, and only factors for which there is variation between different devices of the same type are considered.

All factors are rated on a 10 to 0 scale, with 10 corresponding to the most desirable, and 0 to the least desirable. Some factors are weighed more heavily than others. The sum of the weighted scores for all factors is divided by the total weighing factor, then this result is multiplied by 10 to provide a uniform 0 to 100 performance rating for each device.

Tables 1 through 7 present the performance rating system used for various devices, and Table 8 presents the cost rating systems.

2.2.1 Discussion of Performance Ratings for Individual Categories

Remotely Controlled Lights (Table 1)

Remotely controlled lights were researched on the assumption that they would mounted on a pole or extension device and extended through the cleaning holes in the deck to aid viewing the under-deck structure. For this application the lights were selected based on their horizontal pan and tilt capabilities, their weight, size and the power output. Another important factor includes the transportability of the lights and control system from opening to opening during the inspection.

Various lights were parts of other systems. These lights are not considered remotely controlled lights. They are considered as integral parts of the system they are part of such as a video camera system. The remotely controlled lights section covers only lights that are "stand alone" units. Although these lights are separate from the camera systems, they can often be mounted to work in parallel.

Video Cameras/Video Camera Systems (Table 2)

The video cameras and camera systems were researched based on the weight/size of the camera, power of the light source, weight/size of the system, pan/tilt capabilities, zoom ability and the resolution of the output to the view screen.

The operation of the cameras follow the same assumptions for their use as the lights. The inspection technique uses a camera system lowered down into the tank through the cleaning holes to view the under-deck structure. The inspector is above the inspection tank and can operate the camera and light source by remote control to inspect the under-deck structure and the side structure. The zoom ability and the pan and tilt allow the inspector to get a good view of the surface and welded joints for crack detection as well as view the entire area. The camera and light selection allow the inspector to purchase equipment that fits the

Table 1 Performance Rating Scale for Remote Controlled Lights

	Illum-ination at 50 ft (Ft-c)	Horizontal Pan (deg)	Vertical Tilt (deg)	Length from control (ft.)	Weight (lbs)	Output Power (watts)	Volume (in^3)	Set up/ break down time (hrs)	Moving time (hrs)
Weighing factor > / Rating v	1	2	2	1	2	2	2	1	1
10	2000	375	75	200	5.5	110	300	5 min	1
9	1782	369	67	179	6	103	489	10 min	2
8	1564	363	58	159	6.5	97	678	0.15	4
7	1347	357	50	138	7	90	867	0.25	6
6	1129	351	42	118	7.5	83	1056	0.5	8
5	911	344	33	97	8	77	1244	0.75	10
4	693	338	25	77	8.5	70	1433	1	12
3	476	332	17	56	9	63	1622	1.25	14
2	258	326	8	36	9.5	57	1811	.1.5	16
1	40	320	0	15	10	50	2000	1.75	18
0									20

requirements of the inspection, rather that using a system that has been designed for another type of inspection.

Pre-designed systems have a camera, pan/tilt mechanism, video control unit and a light source. The same characteristics and assumptions mentioned in the camera performance rating apply with the additional information about the systems. The advantage of this system is that all three units are designed for each other and are packaged together with less bulk.

Table 2 Performance Rating Scale for Video Cameras/Video Camera Systems

	Zoom (pwr)	Weight Camera (lbs)	Weight System (lbs)	Volume Camera (in^3)	Volume System (in^3)	Setup/ Break down time (hrs)	Pan Angle (deg)	Tilt Angle (deg)	Resolu-tion (lines)	Light Power (watts)	Time to Move (min)
Weighing factor > / Rating v	2	2	2	2	2	1	2	2	2	1	1
10	20	1	20	38	117	0.1	360	180	700	1000	5
9	18	1.5	26	106	356	0.15	358	170	661	897	10
8	17	2	31	175	595	0.25	356	160	622	794	15
7	15	2.5	37	243	835	0.5	353	150	583	692	20
6	14	3	42	311	1074	0.75	351	140	544	589	25
5	12	3.5	48	380	1313	1	349	130	506	486	30
4	11	4	53	448	1552	1.25	347	120	467	383	35
3	9	4.5	59	516	1792	1.5	344	110	428	281	40
2	8	5	64	585	2031	1.75	342	100	389	178	45
1	6	5.5	70	653	2270	2	340	90	350	45	50
0											

Climbing Inspectors (Table 3)

Climbing inspectors do not have a comparable basis for the type of inspection that they perform. They were researched based on the time they took for the inspection, the planning days and the manpower necessary for the inspection.

Fiber-Optic Video-Scopes (Table 4)

Fiber-optic video-scopes were researched for tankship inspection based on their ability to be mounted on magnetic crawlers and walkers. They also have the ability to be used in pressure vessels and small areas where the inspectors cannot see. They can also be used in small boat and pipe inspections. The criteria that distinguished them apart was the working length, the horizontal/vertical articulation, the diameters and the tip rotation. For tankship inspection ability, the fiber-optic video-scopes were researched based on the field of view, working length, horizontal/vertical articulation, viewable distance and video imaging abilities.

Table 3   Performance Rating Scale for Visual Inspection Using Climbers

	Time (days to inspect))	Setup/ Break Down Time (hrs)	Planning Days	Manpower
Weighing factor >	2	1	2	2
Rating v				
10	1	0.25	0.25	4
9	2	0.5	0.5	
8	4	0.75	0.75	5
7	6	1	1	
6	10	1.5	1.25	6
5	12	2	1.5	
4	14	2.5	1.75	7
3	16	3	2	
2	18	3.5	2.25	8
1	>18	4	2.5	
0				

Robotic Arms and Manipulators (Table 5)

The Robotic arms researched had been developed for specific purposes. The attributes that could relate to the tank ship inspection are the length of the arm, the portable volume, the weight and the rotation of the arm in the horizontal and the vertical direction. The arms were required to maneuver through the cleaning openings and move about the tank with testing devices, cameras or both during the inspection while being controlled by the inspector.

Crawlers and Walkers (Table 6)

Crawlers and walkers were developed for vertical flat plate inspection. This technique could be used to inspect the large flat bulkhead surfaces within tanks but would be of little use on bulkheads with stiffeners present. The ability to carry testing devices on a magnetic climber allows the inspector another option for inspection. The capabilities of the crawlers that were looked at were maneuverability, flexibility, climbing ability, mountable weight, weight of the unit, power requirements, and the operable distance from the control point.

Table 4   Performance Rating Scale for Fiber-Optic Video-Scopes

	Working Length (ft)	Field of View (deg)	Hor. Range (deg)	Vert. Range (deg)	Minimum Depth of Field (mm)	System Weight (lbs)	System Size (in^3)	Bore Rotation	Video Resolution (lines)	Set up/ break down time
Weighing factor >	2	2	2	2	1	2	2	2	2	1
Rating v										
10	100	120	100	230	8	20	410	Y	765	0.1
9	93	117	89	204	9	23	803		714	0.15
8	86	113	78	179	10	25	1195		664	0.25
7	80	110	67	153	12	28	1588		613	0.5
6	73	107	56	128	13	31	1981		563	0.75
5	66	103	44	102	14	33	2373		512	1
4	59	100	33	77	15	36	2766		462	1.25
3	53	97	22	51	17	39	3159		411	1.5
2	46	93	11	26	18	41	3551		361	1.75
1	39	90	0	0	19	44	3944	N	310	2
0										

Imaging Systems (no table)

Imaging systems prove their usefulness in conditions where typical visual techniques can not be used. These conditions include darkness and submersion in oil, water and a mixture liquids. The ability to map the tank efficiently determines the usefulness of the system in tankship inspections. The following systems were researched for their usefulness in tankship inspections:

- Acoustic Imaging
- Microwave Imaging

Sufficient information was not available concerning these systems so a rating scale was not developed.

Table 5 Performance Rating Scale for Robotic Arms/Manipulators

	Length of Arm (ft)	Portable Volume (in^3)	Horizontal Movement (deg)	Vertical Movement (deg)	Setup/ Break Down Time (hrs)	Moving time (hrs)	Manpower	Weight (lbs)
Weighing factor / Rating	2	2	2	2	1	1	1	2
10	60	10000	360	180	0.25	0.25	1	300
9	54	30000	324	162	0.5	0.5		2507
8	48	60000	288	144	0.75	0.75	2	4693
7	42	90000	252	126	1	1		6880
6	36	120000	216	108	1.5	1.5	3	9067
5	30	150000	180	90	2	2		11253
4	24	180000	144	72	2.5	2.5	4	13440
3	18	210000	108	54	3	3		15627
2	12	240000	72	36	3.5	3.5	5	17813
1	6	270000	36	18	4	4	6	20000
0	0	300000	0	0				

Thermography (Table 7)

Thermography involves recording the external structure during a 15 deg change in temperature. From this the cracks and corrosion are thought to have an effect on the release and conduction of the thermal energy. The cameras sensitivity and the monitor's resolution determine the effectiveness of the technique. Its weight and spectral range can be important factors in determining the feasibility of use in ship inspection.

Developmental Technologies

The following categories are discussed, but they are developmental technologies. Their principles have possibilities, but no criteria for performance could be determined. These are described later in this report.

- Elevated-Temperature Laser Ultrasonics
- Polarized Light
- Laser Weld Scanner
- Modal Analysis

Table 6 Performance Rating Scale for Remotely Operated Vehicles - Crawlers

	Step Height Bridgeability (in)	Maneuver-ability (ft)	Setup/ Break Down Time (hrs)	Manpower	Length of Tether (ft)	Weight (lbs)	Volume (in^3)
Weighing factor >	2	2	1	1	1	2	2
Rating v							
10	0.75	On axis	0.25	1	100	10	350
9	0.7	1	0.5		90	11	422
8	0.65	1.5	0.75	2	80	12	494
7	0.6	2	1		70	13	567
6	0.55	2.5	1.5	3	60	14	639
5	0.5	3	2		50	15	711
4	0.45	3.5	2.5	4	40	16	783
3	0.4	4	3		30	17	856
2	0.35	4.5	3.5	5	20	18	928
1	0.3	5	4	6	10	19	1066.9
0							

Table 7 Performance Rating Scale for Infrared Camera Systems

	Low Spectral Range (microns)	Weight (lbs)	Volume (in^3)	Setup/ Break Down Time (hrs)	Video Resolution (lines)	Thermal Resolution (deg)
Weighing Factor >	2	2	2	1	2	2
Rating v						
10	3	1	100	0.1	470	0.02
9	5	2	120	0.15	414	0.05
8	7	3	140	0.25	368	0.1
7	9	4	160	0.5	322	0.15
6	10	5	180	0.75	276	0.2
5	11	6	200	1	230	0.25
4	12	7	220	1.25	184	0.3
3	13	8	240	1.5	138	0.35
2	14	9	260	1.75	92	0.4
1	15	10	280	2	46	0.45
0			300		0	0

Table 8 Cost Ratings

	Cost in Dollars (Interpolate between)					
Rating	Lights	Camera/Systems	Video Scopes	Thermal Cameras	Robotic Arms	Crawlers
1	300	5,000	25,000	1,000	5,000	21,000
2	489	7,333	29,556	3,400	41,111	22,222
3	678	9,667	34,111	5,800	77,222	23,444
4	867	12,000	38,667	8,200	113,333	24,667
5	1,56	14,333	43,222	10,000	149,444	25,889
6	1,244	16,667	47,778	13,000	185,556	27,111
7	1,433	19,000	52,333	15,000	221,667	28,333
8	1,622	21,333	56,889	17,000	257,778	29,556
9	1,811	23,667	61,444	20,000	293,889	30,778
10	2,000	26,000	65,000	25,000	330,000	32,000

2.2.2 Cost Ratings (Table 8)

Benefit/Cost Ratio

An estimate benefit/cost ratio is obtained by dividing the 100 to 0 performance rating by the 1 to 10 cost rating , giving a 100 to 0 scaled benefit/cost ratio. An 100 on the benefit/cost ratio gives the greatest benefit per unit cost and 0 gives the least.

2.3 Commercially Available Inspection Equipment and Methods

The following inspection enhancements consist of commercially available items. They can be purchased or leased based on the requirements of the inspection. These techniques for inspection include remotely controlled lights, video cameras, manipulatable video systems, ROV's, thermographic cameras, and mountain climbing techniques.

2.3.1 Remotely Controlled Lights

Lighting is the most important factor in the inspection process. In "Evaluation of Innovative Inspection Techniques," several theater-type searchlights were identified. These lights are large and heavy, and require extensive electrical supply equipment. Only the smallest can be inserted into a cargo tank through a tank-cleaning opening, and even these are too heavy to be handled without lifting equipment. The study concentrated on small, remotely controlled spotlights with the ability to be mounted on a pole and lowered through the Butterworth opening.

The lights evaluated were primarily designed for use as deck-mounted spotlights for recreational boats. These lights are powered from 12 VDC sources. They are light and small enough to be easily carried, moved, and inserted into tanks through tank cleaning openings. They also have the capability of operating from either batteries or from line power using an AC/DC converter. These lights (along with fiber-optic video-scopes) are the only equipment which was studied that are likely to be owned by the Coast Guard and used directly by Coast Guard inspectors.

Applicability

A light which could be hung from a tank-cleaning opening, powered from a deck-based power source, and controlled remotely by an inspector at the tank bottom would offer two major advantages. First, the inspector would not have to carry the light to the bottom of the tank and back. Second, the distance from the light to the area being illuminated would be shorter, thus providing more light intensity at the target for a given amount of lighting power.

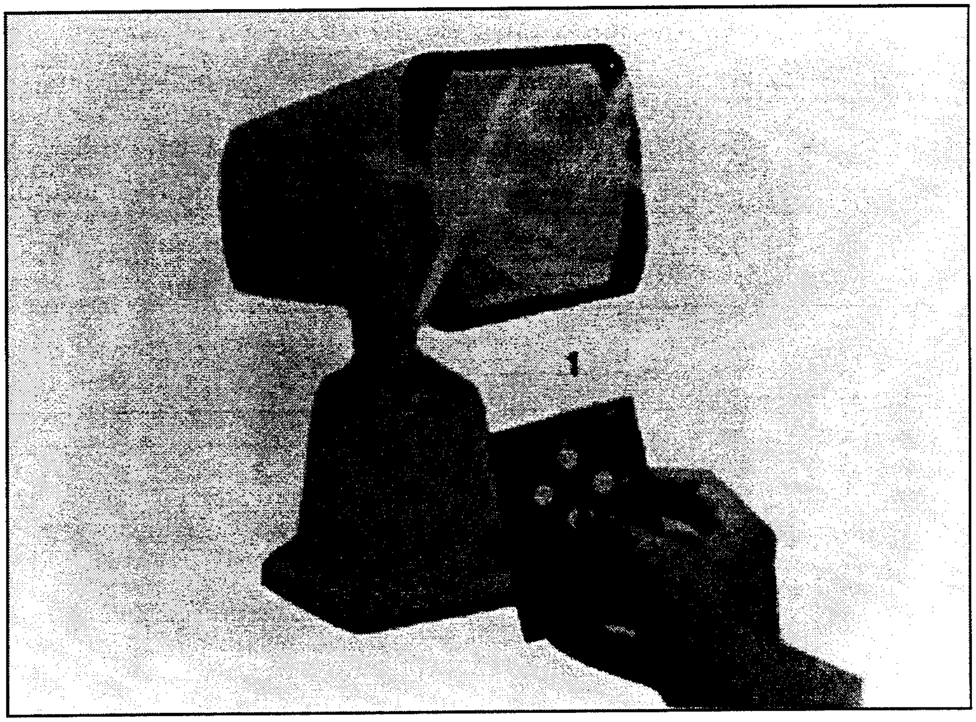

Figure 1 Guest Beamer Remotely Controlled Light

Data

The following lights were considered based on information supplied by the Coast Guard.

Defender Industries, Inc.

Defender Industries, Inc., (800) 628-8225, (914) 632-3001, is a catalog company that lists a light called the Guest Beamer remote control spotlight, Model No. 292-5, Figure 1. The Guest Beamer is a wireless or tethered remotely controlled high intensity light. From the wireless remote the signal can be activated up to a distance of 200 ft from the console. These lights have the following characteristics:

Weight	Dimensions	Volume
8 lbs	10.125 in x 4.25 in x 7 in	301 cubic inches

Horizontal Rotation	Vertical Rotation
355 degrees	40 degrees above to 35 degrees below the horizontal

Power Requirements	Bulb	Output	Illumination at 50 ft (Est)
12 VDC, 7.5 amps	100 watt halogen	1 million candlepower	400 foot candles

Cost
$199.00 tethered - $399.95 for wireless remote light

Defender Industries, Inc. also lists a light called the ACR Remote Controlled Search Light, Model No. RCL-100 B. The ACR search light is a wireless/tethered remotely controlled high intensity light. The light is powered and controlled remotely by a 15 ft extendable cable and has the following particulars:

Weight	Dimensions	Volume	Cost
9 lbs	Not Available	320 cubic inches	$789.95

Horizontal Rotation	Vertical Rotation
360 degrees	None

Power Requirements	Bulb	Output	Illumination at 50 ft (Est)
12 VDC	two 55 watt halogen	5 million candlepower	2,000 foot candles

The Ray-Line 135SL is another light sold by Defender Industries, Inc.. The 135SL search light is a tethered remotely controlled high intensity light. The light is powered and controlled remotely by a 15 ft extendable cable. Particulars are:

Weight	Dimensions	Volume	Cost
8 lbs	7.75 in x 7 in x 6 in	326 cubic inches	$299.00

Horizontal Rotation	Vertical Rotation
320 degrees	75 degrees

Power Requirements	Bulb	Output	Illumination at 50 ft (Est)
12 VDC	50 watt halogen	100,000 candlepower	40 foot-candles

Defender Industries, Inc. also lists a light from Ray Line called the Par Motor Driven Remote Controlled Sealed Beam Light. The Par model 61040-4002 search light is a commercially available tethered remotely controlled high intensity light. The light is powered and controlled remotely by a 35 ft extendable cable. Particulars include:

Weight	Dimensions	Volume	Cost
10 lbs	7 in dia x 13 in	2,001 cubic inches	$469.50

Horizontal Rotation	Vertical Rotation
375 degrees	65 degrees

Power Requirements	Bulb	Output	Illumination at 50 ft (Est)
12 VDC	100 watt halogen	200,000 candlepower	80 foot-candles

Guest, Inc.

Guest, Inc., (203) 238-0550, lists a light called the AFI Halogen Spotlight remote control spotlight, Model M-100. The AFI is a commercially available tethered remotely controlled high intensity light. From the tethered remote the light can be activated up to a distance of 35 ft from the console without a loss in performance.

Weight	Dimensions	Volume	Cost
5 lbs	8.25 in x 9.25 in x 8.75 in	668 cubic inches	$299.95

Horizontal Rotation	Vertical Rotation
360 degrees	80 degrees

Power Requirements	Bulb	Output	Illumination at 50 ft (Est)
12 VDC	100 watt halogen	1 million candlepower	400 foot-candles

Performance Rating

The performance rating for the products are rated on a scale from 1 to 100 using the performance rating chart and the procedure mentioned in the previous section. The cost rating for the products, on a scale of 1 to 10 were determined using the cost ratings in the previous section. The performance rating divided by the cost ratio gives it a benefit to cost ratio listed below.

Table 9 Lighting Performance Summary Table.

Product Name	Performance Rating	Cost Rating	Benefit to Cost Rating
Guest Beamer	83.6	1.4	59.7
ACR Remote Spotlight	67.2	4	16.8
Ray-Line 135SL	52.14	1	52.14
Ray-Line Par	59.64	2	29.82
AFI Halogen	82.14	1	82.14

2.3.2 Video Cameras/Video Camera Systems

In "Evaluation of Innovative Inspection Techniques," several cameras and camera systems were identified. These cameras were light weight and could be mounted on pan and tilt platforms. The cameras could be mounted on poles or mechanical devices and lowered through the cleaning holes to view the under deck structure. The characteristics of the camera that are important are the zoom ability, maneuverability, and the output resolution of the picture.

Also available for the cameras are explosion proof containers for cameras. These containers add considerable weight and could not be lowered through the cleaning openings. Certain Z-purge system camera/camera systems warrant research for intrinsic safety. Most of the cameras are intrinsically safe except for the light source.

In this project, the cameras evaluated were primarily designed for use at close range. The resolution of the picture, the zoom capability and the pan/tilt are the critical attributes to determine the ability of the camera to detect small cracks. These cameras can be powered from 12 VDC or 115 VAC sources. They also have the capability of operating from either batteries or from line power using an AC/DC converter. The cameras are light and small enough to be easily carried, moved, and inserted into tanks through tank cleaning openings.

The video systems consist of a camera with remote controls, incorporated lighting, and a pan/tilt mechanism. External graphics software can control the output to the inspector to provide a clearer, enhanced picture.

Applicability

The principal application for video inspection is in large open spaces such as tankship cargo tanks. The only built-in access is usually a single ladder at one end of the tank leading directly to the bottom. The inspector is often 60 to 90 feet away from important structure such as under-deck girders, transverses, and longitudinals, and from longitudinals high on the side-shell and on longitudinal bulkheads. A deck-based video system might be a valuable adjunct to the typical tank inspection which is conducted primarily from the tank bottom.

There are two existing video systems which have been specifically designed for inspection of tank vessels. There are also similar systems which could be easily adapted for that purpose, and there are many components (cameras, zoom lenses, pan/tilt units, and robotic arms) available which could be combined to form video systems. None of the existing working systems are approved for use in hazardous locations.

While most miniature video cameras could probably be approved as intrinsically safe, none have currently been tested and approved. Intrinsically-safe approval of motor-driven zoom lenses for these cameras or of electrically driven pan-and-tilt units is unlikely.

Explosion-proof enclosures for cameras and explosion-proof pan-tilt units are available. Articulating arms are also available on which cameras could be mounted. None of these are presently approved for hazardous locations. Approval of electrically-operated articulating arms is unlikely.

Data

Visual Inspection Technologies (VIT)

Visual Inspection Technologies of New Jersey has developed a miniature video inspection system incorporating a miniature color video camera with a zoom lens called the Ca-Zoom. The Ca-Zoom video camera is an intrinsically safe video camera. It has a 8:1 power zoom lens and it is rated to a 100 ft depth in water. The camera can be mounted and extended up to 500 ft from the monitor without a performance loss. System particulars are given below. Contact Jim Adams at 800 VIT-LOOK or (201) 927-2900 for additional information.

	Weight	Dimensions	Volume
Camera	1.5 lbs	5 in x 2.75 in x 2.75 in	38 cubic inches
System	16 lbs	9 in x 13 in x 1 in (Controls) 9 in x 13 in x 3.25 in (Battery)	117 cubic inches

Lines of Resolution	Pan Angle	Tilt Angle	Light(s)	Cost
350-460	340 degrees	100 degrees	2-35 watt	$6,000

Visual Inspection Technologies of New Jersey developed a video inspection system called the RPT-400 that was the predecessor of the Ca-Zoom. The RPT-400 video camera is intrinsically safe. It has a 10:1 power zoom lens. The light provides a viewing distance up to 20 ft with the camera. The camera can be up to 500 ft from the monitor without a performance loss. System particulars are given below.

	Weight	Dimensions	Volume
Camera	1.7 lbs	4 in x 5.5 in x 12 in	264 cubic inches
System	7 lbs	9 in x 13 in x 1 in (Control) 9 in x 13 in x 3.25 in (Battery)	497 cubic inches

Lines of Resolution	Pan Angle	Tilt Angle	Light(s)	Cost
460	340 degrees	100 degrees	1-75 watt	$6,000

Bass Electronics Inc.

Bass Electronics has developed an explosion proof camera that is light weight and can fit through the tank cleaning openings. The BE-11 Series Explosion Proof CCTV Camera and the BEPT2361EX Explosion Proof Pan/Tilt components form a possible inspection camera system. It has a fixed lens with no zoom capability. Particulars are listed below. For further information contact Brian Wattigney at Bordewieck Engineering Sales Co. Inc. (617) 659-4915 or Haywood Bass at Bass Electronics Inc. (504) 272-1394.

	Weight	Dimensions	Volume
Camera	9 lbs	11 in x 5.25 in x 12 in	693 cubic inches

Lines of Resolution	Pan Angle	Tilt Angle	Light(s)	Cost
420	355 degrees	180 degrees	None	$11,300

Bass Electronics has also developed a system called the TV-4200 for inspection purposes. The system consists of a PT570P Pan and Tilt unit, a JBPTZ889 Interface Box, a WHPT115F Wiring Harness, a BEPT115LZDT Pan/Tilt/Zoom Control and a TK806 BNC. This Integrated Video system is a Z-purge safe system. It can focus from one meter to infinity and it has a 10:1 zoom lens. The camera has a sensitivity of 0.2 foot-candles. It is rated to a 100 ft depth. Particulars are given below.

	Weight	Dimensions	Volume
System	25 lbs	12 in x 6.625 in dia.	414 cubic inches

Lines of Resolution	Pan Angle	Tilt Angle	Light(s)	Cost
380	350 degrees	90 degrees	None	$8,000

NETS MARICAM System

Northeast Technical Services (NETS) of Cleveland, OH and the British Petroleum Corporation (BP), a major tank vessel operator, have cooperatively developed a video system specifically for inspecting the under-deck structure of tank vessels, Figure 2. The MARICAM system consists of a monochrome video camera with remotely controlled tilt and 20X zoom lens mounted on the bottom of a pole which is extends to 13' below deck level. Panning is

accomplished by manually turning the pole, which is suspended from a tank cleaning opening. An adjustable spot/flood light is mounted above the camera. The system is carried aboard, set up, operated, and moved by two operators. The developer states that structural failures can be detected at a maximum distance of 50 ft.

The video output is viewed by a trained technician on deck, who may be assisted by commercial surveyors or classification society surveyors. When failures or other trouble spots are detected, recordings are made on a VCR as a permanent record. Using the system, a two-man team can inspect the under-deck structure of a tank vessels (70 -80 tank cleaning openings) in 3-4 days.

There is presently one MARICAM system in existence, which is located in Portland, OR. BP and NETS have recently concluded an agreement which will allow NETS to manufacture more MARICAM systems for its own use and to provide inspection services using the systems to other companies. NETS is also now able to sell the MARICAM system. Particulars are given below. For further information contact Jerry Sincotta at Northeast Technical Services (216) 236-9191.

	Weight	Dimensions	Volume
Camera & Support	70 lbs	2 ft x 1 ft x 1 ft	27,648 cubic inches
Remaining System	70 lbs	13 ft long	

Lines of Resolution	Pan Angle	Tilt Angle
470	360 degrees	~60-80 degrees

Light(s)	Cost
1 @ 1,000,000 cp	$80,000 ($2,500/day to rent)

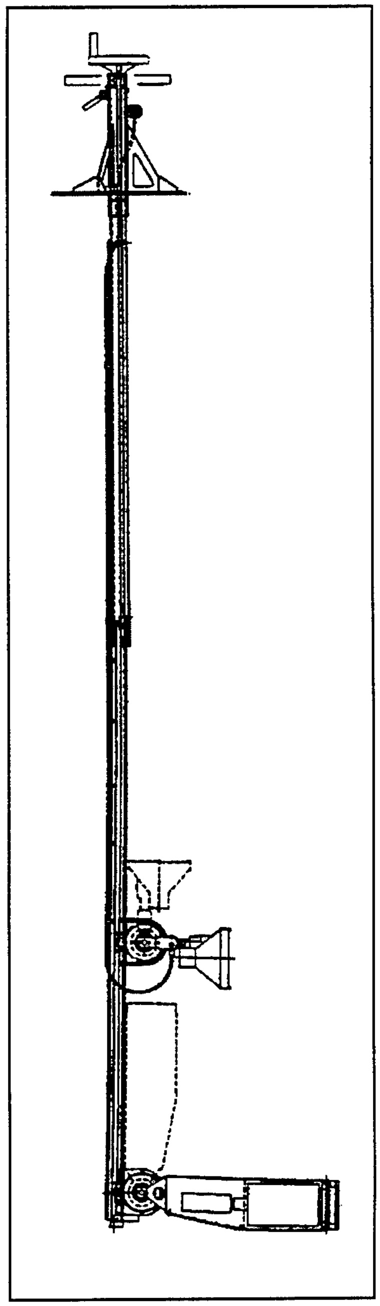

Figure 2 MARICAM Video System

Nisbet RemoteView

Ronald Nisbet and Associates, a commercial marine surveying firm with offices in San Diego, CA, and Portland, OR, has developed a remotely controlled and monitored video system called RemoteView for tank vessel cargo tank inspection, Figure 3. The Nisbet system

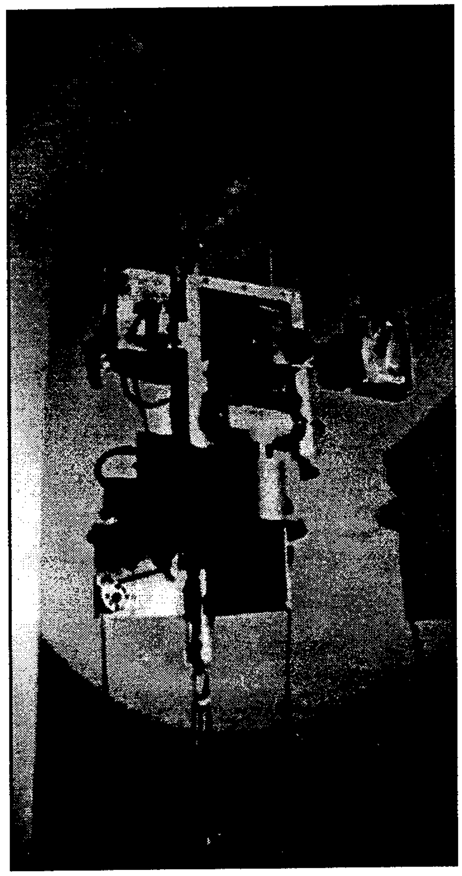

Figure 3 Nisbet RemoteView Camera System

is mounted on a hanging cable and travels up and down the cable, enabling it to cover an entire cargo space from top to bottom. The Nisbet system uses a color video camera with a high power zoom. It has remotely controlled pan and tilt, and coaxially aimed high intensity lights. The RemoteView system must be carried into a tank through the access opening (it will not fit through a tank cleaning opening). Once in the tank it is attached to its cable, which can pass through holes as small as 7/8 in diameter in the deck. It must be manually moved in the tank from one deck opening to the next.

There is presently one RemoteView system, also located in Portland OR. The Nisbet firm plans to use the RemoteView system and any successors in its surveying business, and does not plan to market the systems. Nisbet Associates can be reached at (503) 283-2668.

ROV Technologies Inc.

ROV Technologies has a proposed system called the Refuel Mast Grapple Mounted Camera & Light Inspection System. The camera has a 6:1 or 12:1 power zoom lens. It runs

off a 12 volt DC source. Other particulars are listed below. Contact John Judge at (802) 254-9353 for further information.

	Weight	Dimensions	Volume
System	15-20 lbs	23 in x 23 in x 4 ft	2,116 cubic inches

Lines of Resolution	Pan Angle	Tilt Angle	Light(s)	Cost
700	360 degrees	180 degrees	1-1000 watt	$15,000

Remote Ocean Systems

Remote Ocean Systems has designed a system for inspection purposes that is comprised of two Versa Beam lights, a CE-1 color Camera, a PTE pan & tilt, a IC-10/1 controller and a 75 ft cable. The PT-10 Integrated Video system is not intrinsically safe.
The system needs a 24 volt AC, 60 Hz source. The camera is rated to a 100 ft depth. It can focus from one meter to infinity and it has a 6:1 zoom lens. Other particulars are given below. Contact Robert McCreary at Remote Ocean Systems (619) 483-3902 for further information.

	Weight	Dimensions	Volume
Camera	1.5 lbs	2.3 dia x 7.25 in	120 cubic inches
System	21 lbs	7.6 in x 5.8 in x 3.9 in (pan & tilt) 1.63 dia x 4.7 in (light) 17 in x 15 in x 3.5 in (controller)	1,065 cubic inches

Lines of Resolution	Pan Angle	Tilt Angle	Light(s)	Cost
380	360 degrees	180 degrees	Not known	$14,000

Remote Ocean Systems also has a Miniature Pan and Tilt system, called the PT-5, that is comprised of two 75 watt Mini-Versa Beams and a Miniature Pan and Tilt Camera System. The camera has a sensitivity of 0.2 foot-candles. The camera is rated to a 100 ft depth. It can focus from one meter to infinity and it has a 6:1 zoom lens. Particulars are listed below.

	Weight	Dimensions	Volume
Camera	1.5 lbs	2.3 in dia x 7.25 in	120 cubic inches
System	17 lbs	7.6 in x 5.8 in x 3.9 in (pan & tilt) 1.63 in dia x 4.7 in (light) 17 in x 15 in x 3.5 in (controller)	1,104 cubic inches

Lines of Resolution	Pan Angle	Tilt Angle	Light(s)	Cost
380	360 degrees	180 degrees	Not known	$15,000

Remote Ocean Systems also has an Environmental Camera system that is comprised of two 75 Watt Mini-Versa Beams, a Miniature Pan and Tilt Camera System and an IC-1 controller. The camera has a sensitivity of .2 foot candles. It can focus from one meter to infinity and it has a 6:1 zoom lens. It is rated to a 100 ft depth. Other particulars are given below.

	Weight	Dimensions	Volume
Camera	1.5 lbs	4 in dia x 13 in	653 cubic inches
System	20 lbs	8.7 in x 5.4 in x 4.9 in (pan & tilt) 2.9 in dia x 6 in (light) 17 in x 15.8 in x 3.5 in (controller)	1,329 cubic inches

Lines of Resolution	Pan Angle	Tilt Angle	Light(s)	Cost
380	360 degrees	180 degrees	Not known	$8,500

Symrad Osprey Inc.

Symrad Osprey Inc. has a product called the Cobra 35-ZXR Camera and Cobra 35-ZXR-CCU Control Unit. The Cobra system is not intrinsically safe. It needs a 12-30 VDC, 500 ma, power supply. It is rated to a 50 ft depth. The camera has a sensitivity of 1.5 foot candles. It can focus from 8.8 ft to infinity and has a 6:1 zoom lens. Particulars are given below. Contact Peter Moon at (508) 563-9223 or Symrad Osprey at (619) 471-2223 for further information.

	Weight	Dimensions	Volume
System	26 lbs	8.5 in dia x 10 in	2,270 cubic inches

Lines of Resolution	Pan Angle	Tilt Angle	Light(s)	Cost
470	360 degrees	180 degrees	None	$26,700

Symrad also has a product called the Cobra 35-ZX Camera and Cobra 35-CCU Control Unit. This Cobra system is not intrinsically safe. It uses 12-30 VDC, 500 ma current. It is rated to a 50 ft depth. The camera has a sensitivity of 1.5 foot candles. It can focus from 8.8 ft to infinity and has a 6:1 zoom lens. Other particulars are listed below.

	Weight	Dimensions	Volume
System	24 lbs	8.5 in dia x 10 in length	2,000 cubic inches

Lines of Resolution	Pan Angle	Tilt Angle	Light(s)	Cost
470	140 degrees	130 degrees	None	$22,700

Performance Rating

The performance was rated on a scale from 1 to 100 using the performance rating chart and the procedure mentioned in the previous section. The cost rating for the products, on a scale of 1 to 10 were determined using the cost ratings in the previous section. The performance rating divided by the cost ratio gives it a benefit to cost ratio listed below.

Table 10 Camera Performance Summary Table

Product Name	Performance Rating	Cost Rating	Benefit to Cost Rating
Ca-Zoom	55.9	1.5	37.3
RPT - 400	52.6	1.5	35.1
BE-11	N/A	2.5	N/A
TV-4200	N/A	2.5	N/A
NETS MARICAM System	38.4	10	3.84
Nisbet RemoteView	N/A	N/A	N/A
Mast Grapple Inspection System	78.1	1	78.1
Integrated Video System	56	2.5	22.4
PT-10	68	5	13.6
PT-5	63.8	5.5	11.6
Cobra 35-ZXR	52.4	10	5.24
Cobra 35-ZX	55.2	9	6.13

Figure 4 Climbing Inspector (View 1)

Figure 5 Climbing Inspector (View 2)

2.3.3 Visual Inspection Techniques

Two widely different approaches to the enhancement of simple visual inspections are the use of trained climbers to provide an up-close visual inspection even in hard to reach areas and the use of fiber-optic video-scopes to allow inspections in places where it is difficult or impossible for a person to enter. Inspectors using mountain climbing equipment and techniques can reduce the time and effort of the inspection when compared with current staging or rafting approaches. There are also areas on ships and boats that have inaccessible areas that have commonly been inspected using mirrors. This type of inspection can be modified using video-scopes which are able to fit into small areas and maneuver around obstructions.

Climbing Inspectors

Climbing inspections are conducted by personnel who are trained to use rope-based mountain-climbing or caving techniques and equipment, Figures 4 and 5. Some of this equipment must be specially adapted to inspections of tankship and bulk carrier cargo spaces.

The British-based firm EM&I has developed equipment and techniques in response to the enhanced survey requirements of the International Association of Classification Societies (IACS) for tank vessels and bulk carriers. The enhanced survey requires an "arm's length" inspection of all internal structure, something which can only be achieved by extensive staging. For under-deck structure, such an inspection cannot be achieved by rafting.

Applicability

Climbing inspectors can be used to inspect anywhere where a "safe for entry" condition exists. They are particularly useful for inspecting the overhead and high on the bulkheads of large tanks where staging costs would be very high. By using mountain climbing equipment, the effort involved in setting-up and breaking-down staging or rafting is averted. The climbing inspector is also able to perform portable non-destructive tests and some repairs while at the inspection area.

Data

The EM&I system uses trained climbers who are also qualified structural surveyors and NDT technicians. These climbers not only conduct the arm's-length visual survey, but perform ultrasonic thickness gaging and eddy current testing, as required. The climbers can be equipped with still photography equipment and with helmet-mounted video cameras. They are in constant communication with assistants or surveyors on deck or elsewhere in the space.

EM&I surveys are conducted by a four-person climbing team and are generally planned in cooperation with and witnessed by a classification society surveyor. The classification society surveyor may observe the display from the helmet-mounted camera on a remote monitor and direct the climbers to appropriate locations. The EM&I equipment is not approved for use in hazardous locations; all spaces inspected by these methods must be certified as safe for hot work.

The EM&I visual inspection can take place while underway or in drydock. The company can rig a Powermap 1, 2, or 4 man lift for use in maintenance and repair. The climbing team can rig this lift also so that people without climbing experience can get close to problem areas. A full inspection of a VLCC takes 16-18 days. EM&I can be contacted by calling (022) 477-1077 or (061) 440-8848.

Performance Rating

Only one provider was identified so no performance rating was done. A selection of requirements are listed in the performance rating scale in the previous section. See Table 3.

Fiber-Optic Video-Scopes

Fiber-optic video-scopes use probes constructed of bundles of glass optical fibers to conduct an image from a remote, dangerous, or inaccessible location to a viewing screen in a safe location. The image-carrying fiber bundle may be rigid or flexible. Flexible bundles up to 100' long are possible. Many systems also have built-in lighting coordinated with the tip of the probe. These devices may have flexible or rigid image conduits. The lighting is generally conducted to the probe tip by additional optical fibers of lower quality and greater diameter than those used for image conduction. Most systems using flexible image conduits have aimable probe tips, with provisions for remotely bending the last few inches of the probe to allow coverage of a wider area. Right-angle viewing and lighting attachments are generally available. These attach to the probe tip. Such systems are generally small enough and light enough to be easily portable, although most require an external source of power.

The resolution of fiber-optic systems depends on number and diameter of the imaging fibers. Recent developments in high-resolution miniature video cameras have resulted in hybrid devices which resemble traditional flexible, steerable fiber-optic imaging systems but in which the image is conducted from a miniature video camera at the probe tip (CCD chip) to a color monitor at the viewing end. As with other fiber-optic video-scopes, flexible glass fibers are used to supply light to the probe tip. The CCD chip can be extended to extremely long lengths without much loss in the performance of the imaging system. At these lengths the standard mechanical articulation is not applicable. Only one company has come up with a solution of articulation at lengths greater than 15 ft. Their solution is to control the probe tip by using compressed air.

Applicability

Fiber-optic video-scopes, particular those with flexible image conduits, have a number of potential applications in Coast Guard inspection work:

Pressure Vessels Inspectors are required to conduct internal inspections of pressure vessels such as air receivers and small boilers at periodic intervals. Many of these are too small for an inspector to enter, and even the largest are dangerous to enter. Inspectors presently use mirrors and lights to inspect air receivers, but they find this method only marginally effective. Rigid or flexible video-scopes either with integral lights or using a separate light source are likely to improve inspections of these pressure vessels.

Constricted Spaces Certain small steel vessels such as barges and ferryboats have areas in the rake ends or in the corners of small ballast tanks which are too small for entry and which are difficult to inspect. Inspectors presently use mirrors to inspect many such areas. Flexible video-scopes offer the potential to improve the effectiveness of inspection in such spaces.

Wooden Boats At the July 1994 meeting of the Joint Industry/Coast Guard Working Group on Wood Boat Inspection in Yorktown, VA, one of the major points of discussion was the difficulty which Coast Guard inspectors have inspecting areas of wooden Subchapter T small passenger vessels which are hidden from direct view by interior joiner work, bilge tanks, or other obstructions. Flexible fiber optic-based or video-based scopes might be very useful in certain small-boat inspection situations. They might eliminate the need for more drastic and expensive semi-destructive testing measures, such as removal of planking, which are now used to gain access to hidden structure.

Ballast Tanks on Chemical Tankers The lower levels of ballast tanks adjacent to chemical cargo tanks on chemical tankers, particularly those of foreign registry, are occasionally so hazardous that inspectors will not enter them. Small corrosion penetrations of the lower bulkheads separating the ballast tanks from cargo tanks can allow seepage of a mixture of dangerous chemical cargoes into the ballast spaces.

Ballast tanks, unlike cargo tanks, generally have several platform decks with manholes and ladders between platforms. The manholes usually do not line up vertically from one level to the next. This is a difficult application for remote video imaging, since a camera cannot be simply lowered on a pole or cable from the main deck to the lower levels of the tank. A long-reach flexible video-scope might allow inspectors to do remote close-up inspections of the critical and corrosion-prone areas at least one deck level below where they can climb in safety.

Data

The video image scopes vary in the features. The views can be direct or side. A direct view, observes objects in the path of the scope. A side view, observes objects in the plane at 90 degrees to the path of the scope. Another capability is articulation and rotation. The general range of the articulation is 0 to 120 degrees in the horizontal and vertical directions looking down the shaft. Articulation can be used in the direct view to manipulate the head of the scope, provided there is enough room for movement. Rotation allows the head to be rotated in the plane of the side view and ranges from 0 to 360 deg. The outer diameters of the scopes range from 0.64 mm to 13.5 mm. Working lengths up to 72 ft are available. Viewing the surfaces is governed by the depth of field and the field of view. The field of view gives the angle from left to right that is viewed, and it ranges from 3.7 to 125 degrees. The depth of field is the distance from the scope at which an object is viewable, and it ranges from 1 mm to infinity.

The video scopes have a clear advantage over the older optical scopes where the operator had to look through the eyepiece while moving the rigid scope around. The video scopes provide a larger and clearer image and there is less eye strain. Also, the scope can be

maneuvered into places that it was impossible to view with the rigid scope because the operator no longer takes us space at one end of the scope.

Olympus America, Inc., Industrial Fiber-optics Division

Olympus has a number of video-scopes that are applicable to shipboard inspections. Scope length led to selection of models IV16D2-120 and IV16D2-220 as the most useful.

The IV16D2-120 video-scope has the particulars listed below. It has no articulation. The viewing direction is direct and can have a 360 deg rotational tip. The scope has a 6 dB gain control. Further information can be obtained from Bob Kennedy at (410) 398-3973 and Olympus America Inc., Industrial Fiber-optics Division at (800) 446-5260.

	Weight	Dimensions	Volume
Camera Control	14.3 lbs	13.3 in x 4.4 in x 18.1 in	
Light Source	16 lbs	8.2 in x 5 in x 12.6 in	
Combined	30.3 lbs		1,576 cubic inches

Probe Diameter	Working Length	Field of View	Depth of Field
16.5 mm	39.4 ft	120 degrees	8 mm to infinity

Lines of Resolution	Light Source	Cost
756	ILV-2/300 watts	$53,920

The IV16D2-220 video-scope has particulars given below. It has no articulation. The viewing direction is direct and can have a 360 deg rotational tip. The camera control provides a 6 db gain control.

	Weight	Dimensions	Volume
Camera Control	14.3 lbs	13.3 in x 4.4 in x 18.1 in	
Light Source	16 lbs	8.2 in x 5 in x 12.6 in	
Combined	30.3 lbs		1,576 cubic inches

Probe Diameter	Working Length	Field of View	Depth of Field
16.5 mm	72 ft	120 degrees	8 mm to infinity

Lines of Resolution	Light Source	Cost
756	ILV-2/300 watts	$55,700

The VDS-1 system contains a monitor, VCR, and a mini-camera. System particulars are listed below. The tip has no articulation.

	Weight	Dimensions	Volume
Video Scope	25 lbs	8.5 in x 14 in x 13 in	1,547 cubic inches

Probe Diameter	Working Length	Field of View	Depth of Field
0.5 inches	10 ft	Not known	Not known

Lines of Resolution	Light Source	Cost
460	10 lux	Not known

VIT Inspection Technologies, Inc.

The Fiber Cam 500 video-scope has particulars given below. It has no articulation. Further information is available from VIT Inspection Technologies, Inc. (201) 927-0033.

	Weight	Dimensions	Volume
Camera Control	4 lbs	2 in x 9 in x 13 in	
Light Source	16 lbs	3 in x 4.5 in x 13 in	
Combined	20 lbs		410 cubic inches

Probe Diameter	Working Length	Field of View	Depth of Field
0.5 inches	50 ft	75 x 88 degrees	0.75 inch to infinity

Lines of Resolution	Light Source	Cost
460	300 watts	$24,900

Welch Allyn products (EMCO Intertest Inc., Valtec Systems Inc.)

Valtec Systems has developed a probe system called the VP3 system. It consists of a light source, a camera control unit, and a probe with a camera. The single unit provides camera control, light source, automatic illumination control in one integrated package. Three different probes can be attached to this system. The first probe is the VS228 probe. It is a four way articulating, Longsteer probe. The Longsteer probes require compressed air at 120 psi for articulation. The probe can move left/right 100 deg, 140 deg up and 90 deg down. The second probe is the VS109 probe. It is a four way articulating, Longsteer, LED probe. The LED produces a black and white image. The third probe is the VS225S probe. It is a

non-articulating, LED probe and produces a black and white image. For more information contact Tom Root of Valtec Systems Inc. at (508) 922-2828, Welch Allyn (315) 685-8969 or Tom Daily at EMCO Intertest (201) 927-2900. Particulars are given below.

	Weight	Dimensions	Volume
Combined	36 lbs	8.6 in x 19.6 in x 13.6 in	2,306 cubic inches

Probe Diameter	Working Length	Field of View	Depth of Field
Unknown	100 ft	90 degrees	Unknown

Lines of Resolution	Light Source	Cost
320	Unknown	\$50,850 - \$66,400

Pearpoint products (OPteck Inc.)

Pearpoint produces a video-probe system called the Flexiprobe. The Flexiprobe comprises a camera and a monitor control. The monitor control unit provides control over the focus and the rotation as well as providing a monitor for viewing. Further information can be obtained from Bruce Stetler at (513) 777-1007.

	Weight	Dimensions	Volume
Camera	1.9 lbs	1.73 in dia x 4.37 in	
Monitor Control	42 lbs	18.6 in x 13 in x 16.1 in	
Combined	44 lbs		3,944 cubic inches

Probe Diameter	Working Length	Field of View	Depth of Field
1.73 inches	100 ft	Unknown	Unknown

Lines of Resolution	Light Source	Cost
320	None	Unknown

Pearpoint produces another probe system called the Flexiscan. This consists of a camera, control unit, power supply and joystick unit. The control unit provides control over the focus and the rotation. The power supply controls the light intensity. Further information can be received by contacting Bruce Stetler at (513) 777 - 1007.

	Weight	Dimensions	Volume
Camera	5.5 lbs	2.76 in dia x 8.86 in	
Control Unit	6.2 lbs	13.2 in x 2.4 in x 8.9 in	
Power Supply	22 lbs	14.2 in x 7.1 in x 8.9 in	
Joystick Unit	1.2 lbs	4.7 in x 3.5 in x 5.6 in	
Combined	35 lbs		1,471 cubic inches

Probe Diameter	Working Length	Field of View	Depth of Field
2.76 inches	100 ft	Unknown	Unknown

Lines of Resolution	Light Source	Cost
310	Unknown	Unknown

Performance Rating

Performance ratings for the video-scopes are shown in Table 11. The performance of the products is rated on a scale from 1 to 100 using the performance rating chart and the procedure mentioned in the previous section. The cost rating for the products, on a scale of 1 to 10 were determined using the cost ratings in the previous section. The performance rating divided by the cost ratio gives it a benefit to cost ratio listed below.

Table 11 Video-scope Performance Summary Table

Product Name	Performance Rating	Cost Rating	Benefit to Cost Rating
IV16D2 - 120	60.6	7.25	8.36
IV16D2 - 220	66.11	8	8.26
VDS - 1	54.4	N/A	N/A
Fiber Cam 500	58.3	1	58.3
VPS - VS228	62.78	10	6.278
VPS - VS109	62.8	10	6.28
VPS - VS225S	45.6	10	4.56
Flexiprobe	36.7	2	18.35
Flexiscan	47.2	2.25	21

2.3.4 Flat Plate Inspection Techniques

Flat plate inspections involve the use of video cameras and remote control devices. The cameras have been discussed previously and can be mounted on mechanical arms or crawling/walking devices. Other NDT equipment can be mounted on the same access devices and remotely operated during the inspection.

Robotic Arms and Manipulators

One strategy to extend the range or to improve the image quality of video systems for tank inspection is to move the camera closer to the target once it is in the space. The possibilities for exploiting this strategy are limited in a tankship environment, however, since the 4 or 5 tank cleaning openings in each tank are at best 15" in diameter, and the space directly below the single slightly larger access opening in each tank is obstructed by a fixed ladder, which usually has a landing below the opening. In order for a manipulator to be useful, it would have to be capable of passing through a tank-cleaning opening, extending below the bottom of adjacent under-deck girders, which may be as deep as 10 ft, and then extending a significant distance horizontally. None of the manipulators currently on the market can meet these requirements (Alzheimer, 1994). Long reach manipulators (with reaches up to 50 ft) designed for tasks such as bridge inspection are too heavy to be used without crane support and will not pass through a tank-cleaning opening. Smaller robotic manipulators are available, but these do not have sufficient reach to extend a camera below the level of the under-deck girders.

At least on shipbuilding company is thinking about this issue. One VLCC under construction in Spain offers a: "portable hatch mounted telescopic device for internal inspection of cargo tanks"(Maritime Reporter, May 1994).

<u>Applicability</u>

Use of the robotic arms would allow the inspector to view the areas for inspection, take readings and obtain specific as well as overall views of the inspection area.

<u>Data</u>

Conventional analog, or continuous-motion robotic manipulators require position-sensing equipment to positively establish the position of the device being handled at the end of the arm. Information from these sensors is used as feedback for the control system. The position-sensing systems are often the most complicated and expensive part of a robotic manipulator. In the case of video camera positioning for inspection purposes, exact positioning is not required, and it is possible that much less sophisticated equipment than is currently used for manufacturing robotics could be used.

Another development in simplified robotics has been proposed by Dr. Gregory Chirikjian of Johns Hopkins University (Chirikjian and Burdick, 1993). Dr. Chirikjian has experimented with "binary robotics" in which the arm is a simple arrangement of mechanical links. Some of these links are simple actuators such as air cylinders or electrical solenoids, which have only two possible lengths, short and long, and whose lengths are accurately controlled by stops at each extreme of travel. In a linkage of this type, the position of the end is accurately inferred from the actuating signals sent to the actuating links, without the need for any type of position-sensing or feedback control system. This technology offers the possibility of low-cost accurate-positioning robotics at the expense of a finite number of possible positions. In positioning a pan/zoom/tilt camera unit, the limitation on the number of possible positions would not be a serious drawback. Present designs are for two-dimensional manipulators, but the technology could be extended to three dimensions. Two-dimensional manipulators would be adequate for a deck-based video inspection system, since manual angular positioning is practical in this application.

SONSUB

SONSUB has developed a prototype bridge inspection system for the Department of Transportation based on a mechanical arm. This integrated system is comprised of a truck bed with an extendable arm that can extend to 60 ft and contract to 16 ft. The largest transport dimensions, not including the truck, are 10 ft x 4 ft x 6 ft. The maneuverability is a straight 60 ft extension down with a 30 deg movement left and right of the center. The boom also swings forward 30 deg and back underneath itself 15 deg. The volume and cost were not available. For further information, contact SONSUB at (713) 984-9150.

A second product of SONSUB is the Cascaded Manipulator System. This integrated system is comprised of a truck bed with an extendable arm that can extend to 39 ft and has a manipulator which is 5.85 ft long. The largest transport dimensions, not including the truck, are 10 ft x 4 ft x 6 ft. The unit has a straight 39 ft extension down with a 360 deg horizontal movement and a 180 deg vertical movement. It also has stabilizers and video camera visual feedback for remote operation. The volume and cost were not available.

Western Space and Marine

Western Space and Marine has a product called The Arm MK-37. The Arm consists of a four link mechanical arm. Its reach is maximum reach is 5.5 ft. The weight of the arm is 320 lbs and the range of motion is limited by the linkage arrangement. The dimensions were approximately 30 in x 12 in x 6 in. The cost of the arm and control system is approximately $330,000. The power requirement are 24 volts DC at 25 amps and a Hydraulic power of 3,000 psi. This arm is too short for practical purposes but could be used to demonstrate the

performance of multiple link robotic arms. Western Space and Marine can be contacted by calling (805) 963-3831.

GEC Alsthom

GEC Alsthom has many products such as the ASM, MARA, ADM, Heavy Duty Manipulator, Interstitial Manipulator, Hinkley Point Manipulator, Sizewell Multilink Manipulator and the Long reach Manipulator. All of these products originated from a specific design for a specific purpose. These purposes include pipe travel for inspection and heavy unsafe manipulation. The maximum reach of these manipulators is 30 ft of the ADM. The lightest weigh mentioned was the GT15 master slave manipulator at 264 lbs, and the corresponding reach is 39 inches.

The longest arm produced by the US division of GEC Alsthom is the ESM/Titan2. The reach of the arm is 32 ft when the Titan 2 and the ESM arm are connected. The overall weight of the system is 10,400 lbs and it has a portable volume of 223,695 cubic inches. The arm consists of a 12 ft bending segment, a 13 ft bending segment and an articulating 7 ft arm. Schilling Development can be contacted through Roger Anderson at (916) 753-6718 for more information.

Performance Rating

The performance of the products was rated on a scale from 1 to 100 using the performance rating chart and the procedure mentioned in the previous section. The cost rating for each product, on a scale of 1 to 10 was determined using the cost rating scale in the previous section. The performance rating divided by the cost ratio gives it a benefit to cost ratio listed below.

Table 12 Robotic Arms Performance Summary Table

Product Name	Performance Rating	Cost Rating	Benefit to Cost Rating
Bridge Inspection	42.3	N/A	N/A
Cascaded Manipulator	71.8	N/A	N/A
ESM/Titan2	74.3	10	7.43
MK-37	64.6	N/A	N/A

Crawlers and Walkers

Crawlers and walkers are remotely controlled robotic devices that can magnetically attach to the inspection surface. They can support NDT equipment and cameras, be programmed for a multitude of tasks, and can be remotely controlled by the inspectors for visual inspections. For ship inspection, the crawlers and walkers are required to scale the vertical walls and travel on the overhead. Magnetic crawlers were researched based on their ability to hold to the side of the steel ships using a magnetic force. Another type of climber that operates on suction to the wall was mentioned in the furnished information. Based on the existence of oil residue and the inability for the suction to operate on areas of corrosion they were dropped from consideration.

Applicability

Development of new inspection techniques may allow for crack and corrosion detection from the external shell. The walkers and crawlers can be magnetically attached to the side of the ship and programmed to inspect the hulls internal structure using mounted devices. Along with a position tracker the crawler could detect and locate a crack or fracture completely remote from the inspector. The inspector could then verify the failures using the same crawler or by close-up visual inspection.

Data

EMCO InterTest Inc.

EMCO InterTest Inc. has developed a crawler called the MWC 4200S. The MWC is a steerable magnetic wheel crawler designed for high speed remote thickness measurement,

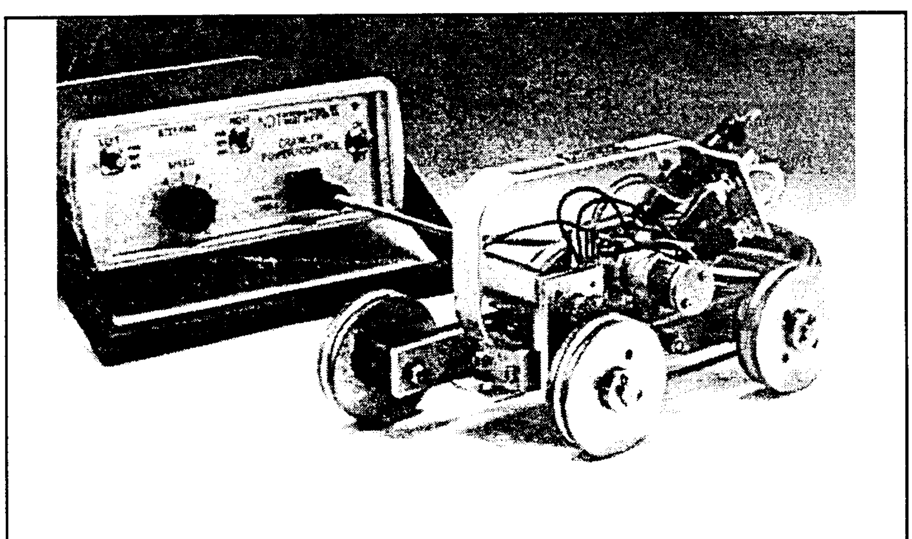

Figure 6 NDT Crawler

using ultrasonics, of steel tanks. It uses water as the coupling media. Remote inspections such as ultrasonic flaw detection and eddy current tests are possible. It can also be equipped for weld inspection. It requires 110 VAC, 60 Hz to operate, and is 20 in x 3.5 in x 5 in with a weight of 14.5 lbs. The cable length is 100 ft. It is capable of climbing over a 1/2 in step. It has a top speed of 15 ft/min and it has a turning radius of 5 ft. Cost was estimated to be $28,000 with out tracking and $32,000 with tracking. For further information, contact Tim Daley at EMCO InterTest Inc. (201) 927-2900.

NDT International, Inc. NDT International, Inc. has developed a crawler called the Magnetic Crawler Inspection System, Mark IV-B, Figure 6. The magnetic crawler is powered by a 110 VAC current or a 12 VDC power source. The crawler takes ultrasonic measurements of plate thickness and can extend, using a tether, to 100 ft. The cost for the existing crawler and communication package was quoted at $22,450. The weight of the system is under 10 lbs. Its dimensions are 12 in x 9 in x 8 in. It can bridge a max step of 0.75 inches. The crawler can turn around on its axis within its own length. At the present time, this crawler can only be fitted with an ultrasonic thickness gage. Victor Kelly at NDT International, Inc. (215) 793-1700 or NDT International at (610) 793-1700 can be contacted for further information.

Visual Inspections Technologies (VIT)

Visual Inspections Technologies has developed a crawler called the DX-20 Inspection System, Figure 7. The Magnetic crawler is powered by a 110 VAC current or a 12 VDC

Figure 7 VIT Crawler

power source. The crawler takes ultrasonic measurements of plate thickness and can extend, using a tether, to 100 ft. The cost for the existing crawler and communication package was quoted at $27,500. The weight of the crawler is 17 lbs and its dimensions are 23.25 in x 11.125 in x 4.125 in. The crawler can rotate on its axis. Contact Shannon Hanson at VIT (201) 927-0033 for further information.

Performance Rating

The performance of the products was rated on a scale from 1 to 100 using the performance rating chart and the procedure mentioned in the previous section. The cost rating for each product, on a scale of 1 to 10, was determined using the cost rating scale in the previous section. The performance rating divided by the cost ratio gives it a benefit to cost ratio listed below.

Table 13 Crawlers Performance Summary Table

Product Name	Performance Rating	Cost Rating	Benefit to Cost Rating
MWC-4200s	73	10	7.3
Mark IV-B	98	2	49
DX - 20	58	6	9.7

2.3.5 Imaging Systems

Acoustic Imaging

For this study, acoustic and microwave imaging systems were investigated. Unlike light-based imaging techniques, both of these technologies are potentially useful in darkness, very turbid water, and possibly in other liquids such as oil. This type of device is being evaluated in a parallel program at the R&D Center which is evaluating sensors for use on remotely operated vehicles to assess hull damage (Bradley, et.al., 1993 and Naval Surface Warfare Center, 1995).

Acoustic imaging, or sonar imaging, uses an active sonar technique in which a sound beam is emitted toward the target surface and the returning echoes are received by an array of transducers and electronically transformed into a visual image of the target. The technique has been used very effectively to create images of the sea bottom with forward-looking and side-scan sonar.

Applicability

The most promising potential use of acoustic imaging is in assessing gross damage to vessels which might result from grounding or collisions. Acoustic imaging equipment could be used either inside or outside a vessel, in any combination of water and oil, to assess the extent of gross structural damage and the size of large holes in the vessel's skin. Acoustic sensors could operate in many environments in which divers or remote visual imaging systems could not function.

Data

Sonar imaging is very effective at detecting the topography of an uneven surface, but is much less effective at showing defects such as holes or cracks in a flat surface. The resolution is limited to the smallest possible array element spacing, which is on the order of 0.25 inch. In order to utilize this resolution, however, there would have to be a 1:1 mapping between the sensors and the surface, which would require an inordinately large time to scan a large surface, and would lead to serious difficulties in establishing the position of images. In practice, the sensor array would map to a target much larger than the array itself, with a resulting resolution larger than the array spacing. It is unlikely that a practical acoustic imaging system could detect small flaws such as cracks or failed welds in a flat surface even if the sensors were very close to the surface and covered only a small target area. It is even less likely that such a system could detect failures at welds between two perpendicular surfaces, which is where weld failures often occur in ships.

Performance Ratings

The performance ratings on the acoustic imaging systems have not been determined because there is no commercially available system which can be utilized inside of a tank. In addition, initial evaluation (Bradley, et.a.,1993) indicate that the resolution will probably not be sufficient to detect small defects, only gross distortions of the structure.

Microwave Imaging

The principles of microwave imaging are similar to those of acoustic imaging. Microwave imaging devices would also require an remotely controlled arm or vehicle to bring the sensor close enough to the target. Microwaves, like acoustic energy, can penetrate oil or water. As with acoustic imaging, resolution is also dependent on the spacing of the sensing elements in the sensing array.

Applicability

The most promising potential use of microwave imaging is in assessing gross damage to vessels which might result from grounding or collisions. Microwave imaging equipment

could be used either inside or outside a vessel, in any combination of water and oil, to assess the extent of gross structural damage and the size of large holes in the vessel's skin. Microwave sensors could operate in many environments in which divers or remote visual imaging systems could not function.

Data

Microwave imaging might be useful if it can provide better resolution than acoustic imaging techniques at similar ranges. Like acoustic imaging, its primary advantage would be the ability to operate in oil, in very dirty water, or in mixtures of oil and water, all situations in which visual imaging techniques would not work well or at all.

Performance Rating

The performance ratings on the acoustic imaging systems have not been determined yet due to the fact that no system is commercially available.

2.3.6 Thermography

Thermography uses infrared sensors (either conventional film or video) to provide a thermal image of an object. Areas with have different temperatures emit different amounts of infrared energy and the imaging system shows the temperature differences as color differences (or shades of gray). Video-based systems can resolve temperature differences as low as 0.02 degree Celsius. The operating temperature ranges available easily cover all imaginable uses for inspection of fabricated steel structures. Thermography has been used with great success in inspecting composite materials for hidden internal flaws, but to date, it has not been used for inspecting large fabricated steel structures such as ship. It has been used in a laboratory setting (CNDE, 1994) to detect water between piping and insulation when heated with a microwave source.

Applicability

While thermography equipment is commercially available, the applicability to vessel inspection is clearly developmental. The potential use of thermography in vessel inspection is in identifying, from outside a vessel, the locations of internal structural members and possibly evaluating the soundness of welds connecting those structural members to the shell plating. It is unlikely that thermography could be used effectively to identify flaws in the shell plating. Flaws in shell-type structures such as composite panels are often detectable by thermography when the plane of the flaw lies perpendicular to a heat flow path across the thickness of the shell(Jones, et. al., 1993 and Zalameda, et.al.,1994). With a steel vessel, flaws in the shell will be generally parallel to heat flow paths across the shell plating, and would most likely not be detectable. The questions of whether underlying structure could be detected through the

7/8 in to 1-1/4 in thick shell plating common to tank vessels and of whether defects in that structure will be detectable will have to be answered by laboratory or field testing.

In the principal strategy for the use of thermography in inspecting structures, a static temperature difference is maintained between the atmosphere or fluid inside a structure and that outside. As heat is conducted from the hot side to the cool side, variations in the thickness of the wall of the structure, the presence of structural framework, or certain types of defects perpendicular to the path of heat flow will cause variations in the temperature of the outside skin. If these variations are large enough, the thermal image of the skin will show differences in color, which can be used to identify the location of underlying structural components and might possibly be used to assess the connection between the underlying structure and the skin. In order for this strategy to be effective, some means of maintaining an inside/outside temperature differential is necessary. This requirement would make this strategy difficult to implement on a structure as large a tank vessel.

A second strategy uses the same principles as the first, but uses the transient conditions caused by fairly sudden ambient temperature changes of the environment, such as occur at dawn and dusk, or by changes in the solar radiation striking the surface. Those areas which have structure or defects behind them will change temperature at a different rate than other nearby sections, and thus, during the transient period there may be a detectable temperature difference which would show underlying structural components. A transient method, call Time-Resolved Infrared Radiometry (TRIR) has been shown to detect hidden (second layer) corrosion in aircraft structures (CNDE,1994).

Because of the time required for developing conventional film, video imaging systems, which give immediate indications, are clearly preferable, even though they are expensive. In theory, a video scan of the side of a vessel, taken from the outside, would show the locations of the longitudinal stiffeners as thin lines having a different temperature. If there was a flaw in the connection between a longitudinal and the shell, as occurs when a weld fractures, this might be visible as a discontinuity in the lines indicating the longitudinals.

The most likely use of thermography would be to scan the above-waterline portion of the side of a vessel for locations where the welds between the longitudinals (or the web frames or transverse bulkheads) and the side-shell had failed. The equipment would be set up on a pier or on an adjacent vessel, and after an event which would cause a transient temperature condition on the side of the vessel, the side would be scanned. The image would be recorded on video tape and replayed either immediately or later, as required. The thermal transient could be caused by a fairly rapid atmospheric temperature change at dawn or at dusk, or by the side of the vessel suddenly coming into sunlight or falling into shadow either by the sun's movement, by turning the ship, or by casting a shadow artificially on a portion of a sunlit side of the ship.

A typical standard magnification video lens used in thermography gives a vertical angle of view of about 10 degrees which, with a vertical resolution of 450 lines will provide an target size about 11 ft high with each screen pixel representing a 5/16 in square on the target surface. In order to cover a larger target, the camera can be moved farther away or a wide-angle lens can be used, but the area imaged by each pixel will increase accordingly. The wide-angle lens is probably the better choice for an application where only small differences in temperature are expected, since convection currents in the air between the target and the camera can cause interference, and the potential for these kind of problems increases with greater target distance.

<u>Data</u>

VideoTherm

VideoTherm has thermographic cameras from their 91, 92, 96, 300 series. The VideoTherm 91 System uses a 12 volt DC battery or 115 VAC AC power. The infrared spectrum ranges from 8 - 14 microns. The battery operates for 90 minutes on a full charge. The cost ranges between $14,000 - $24,000 for these systems. The thermal resolution is 0.15 degree Celsius at an ambient temperature of 25 degrees Celsius. The range of dimensions of the various cameras are between 4.55 in x 4.55 in x 10.7 in and 10 in x 4 in x 6 in. The weight varies in the range of 5 - 6.63 lbs. The power sources measure 8.37 in x 1.72 in x 10 in and weigh from 4.4 lbs to 12.65. The camera contains recursive filters at 5, 8 and 12 decibels. The output to video is 272 lines of resolution. They have 25, 50 and 75 mm lenses and operate on 7 watts of power. The video image can be enhanced, using software, to locate smaller thermal differences. The thermal differences require a 15 degree change in temperature between the inner and outer hull for the most accurate view. Contact Brett Monroe or Bruce Monroe of Monroe Infrared Tech at (800) 821-3642 for further information.

Cincinnati Electronics Corp.

Cincinnati Electronics Corp. has Thermographic cameras called the IRC - 160/160st, TVS - 2000/st/te. The Cincinnati Electronics cameras temperature resolution range from 0.02 to 0.05 degree Celsius. They provide a picture with 256 grey scales and 300 lines resolution using an 120 VAC source. The respective dimensions are 9.75 in x 4.13 in x 9.5 in, 14.5 in x 4.75 in x 5.25 in, and 11.3 in x 4.5 in x 5.5 in, with weights from 8 to 9 lbs. Cost is around $20,000 for each of the systems. Contact Cincinnati Electronics Corp. at (513) 573-6275 or Black & Associates at (410) 472-2416 for further information.

Tritek Inc.

Tritek Inc. has a thermographic camera called the 5480. The 5480 system has a temperature resolution of 0.2 degrees Celsius at an ambient temperature of 25 degrees Celsius. Output is displayed at a video resolution of 300 lines. The dimensions are 4 in x 3.5 in x 11

in with a 4.7 lb weight. Cost is $20,000. Contacting Jim O'Hanley at Tritek Inc. (617) 272-4550 for further information.

FSI Flir Systems

FSI Flir Systems has a thermographic camera called the High-Resolution Hand-Held Thermal Imaging Camera. The FSI system operates in the 3-5 micron spectral range and has a discernable temperature difference of 0.1 degree Celsius at 30 degrees Celsius ambient. It has 256 grey scales and outputs 320 lines. The camera measures 9.25 in x 5.9 in x 5 in with a weight <8 lbs. Cost is $32,000. FSI Flir Systems can be contacted by calling (800) 322-3731 or (503) 684-3731.

Performance Rating

The performance of the products was rated on a scale from 1 to 100 using the performance rating chart and the procedure mentioned in the previous section. The cost rating, on a scale of 1 to 10, was determined using the cost rating scale in the previous section. The performance rating divided by the cost ratio gives it a benefit to cost ratio listed below.

Table 14 Thermographic Camera Performance Summary Table

Product Name	Performance Rating	Cost Rating	Benefit to Cost Rating
VideoTherm 91,92,96,300 series	60.9	7	8.7
IRC-160/160st	57.3	8	7.84
5480	72.7	8	9.0875
FSI Thermal Imaging Camera	68.2	9	7.57

2.4 Developmental Equipment and Methods

The following methods, represent some new theories that could have an application to ship inspection. These methods are not commercially available, but most have been tested and can be demonstrated. There are no performance ratings for these techniques because the have not been developed sufficiently for accurate assessment of their potential.

Four other technologies were investigated. These are laser ultrasonics, surface characterization by polarized light, laser weld scanning, and modal vibration analysis. These are all developmental technologies and equipment is not commercially available. Their optimum usage is to mount them to an ROV, crawler or on a mechanical arm for inspection purposes. In all cases, the technology and equipment can be demonstrated in a laboratory setting, and in a few cases could be brought into the field.

Elevated-temperature laser ultrasonics does not appear to have any usable applications in inspection of steel structures at room temperature.

Polarization techniques and modal analysis are likely to be effective, but field applications are certain to be logistically difficult. Laser weld scanning is unlikely to be an effective technique for finding failed welds.

Elevated-Temperature Laser Ultrasonics

Laser ultrasonics uses the impact of an instantaneous thermal shock produced by a pulse of a laser at a certain frequency on a metal surface to produce an ultrasonic sound wave through the material. An optical interferometer is mounted at the surface and records the ultrasonic vibrations produced to map the ultrasonic vibration signature and determine the properties of the material. Currently the use of a single laser has been abandon due to the size and inefficiency. Now, ten small powered lasers are used to produce the same results with the dimensions of 3 ft x 2 ft.

Applicability

Elevated Laser Ultrasonics is being researched by Dr. Robert Green Jr. at the Center for Non-Destructive Evaluation of Johns Hopkins University ((410) 516-6115). The principal use to this date is in determining an image of the section tested. From this image cracks and thickness of the material can be determined. The technology shows great promise in determining the average through-thickness temperature of thick metal sections at elevated temperatures. This information is critical to the control of quality in processes such as forging (Center for Nondestructive Evaluation, 1994).

The developers of the technique have indicated that a derivative of the laser ultrasonic technique could be used to remotely identify surface defects and subsurface flaws in metal plating. This is presently a capability which can only be demonstrated under laboratory conditions. This system is still under test and the results will be presented in a later report.

Polarized Light

When a beam of polarized light reflects off a flat surface, part of the reflected beam becomes unpolarized. When the polarized light encounters corrosion, light is reflected back

still polarized. The polarization vision technique measures the polarization of the reflected beam to enhance a visual image of the surface. The principal use is in enhancing the edge-contrast of photographs or video images of objects. A related technique is the proprietary Diffracto-Sight technology, which uses a twice-reflected beam of polarized light to provide an vertically exaggerated image of the surface topography.

A second application of the polarization vision technique, and the one of most interest to ship inspections, exploits the principle that the degree of polarization acquired by an unpolarized beam of light reflecting from a surface depends upon the electrical conductivity of the surface. Beams reflected from insulating, or dielectric surfaces become more polarized than do beams reflected from conducting materials. Measurements of the amount of polarization of the reflected beam can be used to predict the nature of the material from which the beam has reflected. The developer of the polarization vision technique has proposed and experimented with using this phenomenon to assess the integrity of surface coatings on flat steel surfaces. It is claimed that the technique can detect the presence of corrosion under paint films which still appear to be sound on the surface. The equipment required is a light source and a polarization-sensing camera, which are positioned to view a small area of the surface to be inspected.

The existing polarized vision system consists of a liquid crystal polarization camera developed for underwater use. The weight of the camera was 1-2 lbs, it had a waterproof housing and uses a 9 volt DC power source. For non-submersible application the polarizer and two liquid crystal lenses can be mounted to any CCD camera, given the size of the lens screw thread diameter and the requirement that the front of the lens does not rotate the liquid crystals during the zooming process. Another requirement is that the light source provides polarized light. This can be achieved by passing the light through a polarized filter. The Liquid Crystal lens weighs approximately 1-2 ounces. A short description of the process is a follows:

> The light is output from the light source and passed through a polarized filter that is approx 38 percent transmissive. The light reflects off of the surface and back into the Polarizer/Liquid Crystal lens. On a painted surface, scratches and corrosion do little to diffract the polarized light, whereas the paint diffracts the polarized light greatly. The lack of diffraction of the scratches and corrosion sends pulsating polarized light back at the camera. From the video resolution, areas of corrosion show up as noticeable pulsations through the inspection monitor.

The same idea can be used for the shiny or flat steel surface, but in reverse. It is thought that the uncoated steel surface will return a great amount of the polarized light to the camera, whereas, the scratches and corrosion will return significantly less. In this instance, the video output would be searched for dark spots/areas for possible cracks or corrosion.

This lens can be attached to an inspection camera and the polarization of the lens can be electronically controlled to toggle the corrosion detection capability. The light source could outfitted to toggle the polarization also.

Applicability

Polarization vision is being researched by Dr. Larry Wolff of Johns Hopkins University, (410) 516-8710(Wolff, 1994 and Wolff and Mancini, 1993). The technique might be used to scan a large flat surface, such as the interior bulkheads and bottom of a cargo tank on a double-bottom tank vessel to evaluate the integrity of the coating. The final development of a ship inspection unit would combine the camera, the polarizer lens and the polarized light source onto a remote controlled manipulatable arm. This system would be used to determine cracks and corrosion on the longitudinal welds and the surfaces. This technique was also testing in the hull damage project at the R&D Center (report to be published, 1995)

Laser Weld Scanner

The laser weld scanner is a computerized imaging device in which the image is analyzed by a computer, rather than displayed to the operator, printed, or recorded. The scanner is moved along the weld, and records information about the surface of the weld, which is used to predict the quality of the weld. The device is primarily intended to take the place of, or supplement, radiography and other NDT techniques for quality control of new welds. It uses the pattern of ridges perpendicular to the axis of a weld to predict the likely soundness of the weld by comparison to the patterns for known sound and unsound welds.

Applicability

Laser weld scanning is being researched by Dr Graham Edwards and Mr. Harvey Costner of the Navy Joining Center (NJC) being run by the Edison Welding Institute, (614) 486-9400, under a US Navy contract. The procedure analyzes the patterns of the perpendicular ridges of the weld. It is unlikely to be useful for finding parallel features, such as cracks, unless they are large, separated fractures. This technique is essentially another close-range non-destructive weld testing technique, rather than an overall scanning technique. It appears to be useful for new construction or repair but the cleanliness required may not make it suitable for in-service inspection.

Modal Analysis

Inspectors have traditionally tested fabricated steel structures by "ringing" individual components with a hammer. When there are a number of components of similar section and length and having similar conditions of fixity, the hammer method provides a quick way of flagging potentially deficient components by the audible difference in the ringing sound of an defective component compared to that of the majority of non-defective components. The

presence of damping material (i.e. crude oil sludge) can considerably decrease the effectiveness of the ringing technique.

Modal analysis extends the concept of the "ringing" test by using an instrumented hammer to deliver the blow, a precision transducer or accelerometer to measure the response of the member, and electronic signal conditioning and computerized signal analysis to analyze both the response spectrum and the vibrational modes of the tested component.

In the modal analysis, there are two basic procedures. The first requires that baseline measurements be taken for each member when it is new or when it is known to be in good condition and properly attached to the adjoining structure. The results of measurements taken during an inspection are compared to the results of the baseline measurements. (A measurement of one component may be suitable as a baseline measurement for a number of a number of components have similar sections, lengths, and conditions of fixity.) A significant difference between either the response spectrum or vibrational modes of the baseline and current readings indicates either a major change in the section (such as due to corrosion) or in the conditions of fixity (such as a failed weld). The second procedure merely compares existing repetitive structures and looks for the anomaly among them, assuming that the minor differences between them are insignificant. There are several obvious limitations, and also several unknowns, in the extension of modal analysis to tankship hull structure.

The principal limitations of modal analysis are that each individual structural member must be tested independently, that reliable baseline readings must be available for each member tested (or possibly for types of members), and that the placement of the transducer and hammer must be done accurately and repeatable when taking both the baseline readings and the later comparison readings. This is the same limitation put on any kind of NDT technique which attempts to cover the entire vessel.

Applicability

Modal analysis is being researched by Dr. David F. Mazurek of the Coast Guard Academy, (302) 444-8530. Its potential application to tank vessel inspection is in evaluating the condition of the longitudinal structural members which are attached to the bottom, side-shell, and deck (Mazurek, 1994). In this application the transducer and hammer unit would be attached to each section of each longitudinal. In a typical tank vessel there are approximately 160 to 200 longitudinal members in the cross-section. The longitudinals are welded to the oil-tight and watertight transverse bulkheads. They are also welded to the intermediate web frames and to stiffeners on those members. Thus, each span of each longitudinal is essentially fixed at each bulkhead and web frame. Each span would be tested independently if a 100% inspection is required.

For a typical tank vessel with six cargo blocks (each containing two wing tanks and one centerline tank) and with three sections (defined by web frames in the wing tanks or by main

transverses in center tanks, in each block) there would be approximately 3000 individual longitudinal spans to be tested. Assuming that six hours of each day would be devoted to testing (the remainder to moving equipment), and an average time of 5 minutes to instrument a member, make the test, confirm the results, and to move on to the next member, it would take 42 working days, or about two calendar months, to test one ship. The test crew would require close-up physical access to each longitudinal in order to conduct the tests, which would require staging or the use of climbing techniques. This time would again be required for any other type of NDT technique if 100% coverage is required.

In addition to the obviously time-consuming nature of modal analysis, There are several issues which remain to be answered by further research:

- It appears that the method is not sensitive to small defects but it is not clear as to what size of defect detected is comparable to that for visual inspection.
- It is not clear how sludge or other accumulated material affect the results of modal analysis. There may be uncertainty when comparing to clean baseline data as well as when comparing to other structural members.
- This method may not detect localized reductions in section due to corrosion. It is also not clear what constitutes a major change in cross section and how a much of a change is comparable to the impact of a major defect.

2.5 Summary and Conclusions Based on Technology Review

2.5.1 Remote Controlled Lights

Remotely controlled lights were evaluated on the assumption that they would mounted on a pole or extension device and extended down through the cleaning holes to view the under-deck structure. For tank ship inspection applications, the lights selected for further research were the AFI Halogen and the Guest Beamer. The AFI Halogen light is a commercially available tethered remotely controlled high intensity light. From the tethered remote, the light can be activated up to a distance of 35 ft from the console without a loss in performance. The horizontal pan and tilt capabilities allow for more viewing angle than the others that were researched. The weight is 8 lbs which allows for the light to be manually used with a pole extension and lowered through the Butterworth openings. The major limitation of the light is the remote operation limitation of 35 ft.

The Guest Beamer was also selected for further research. The performance was similar to the AFI and the ability for the light to be remotely controlled via radio from two hundred feet was a significant advantage. This function that would save time and effort in the moving

the light during the inspection. Both lights have the same power output, are easily transportable, and are small enough to fit through the Butterworth openings.

2.5.2 Video Cameras

The video cameras were researched based on their weight, pan/tilt capabilities, zoom ability and the resolution of the output to the view screen. The operation of the cameras follow the same assumption for their use as the lights. The inspection technique uses a camera system lowered down into the tank through the cleaning holes. The inspector is above the inspected tank and operates the camera system by remote control to inspect the under-deck structure and the side shell longitudinals. For this application the Mast Grapple Camera system was selected as the best candidate for further research. The Mast Grapple system has the highest available zoom power (12:1), but needs to be tested to verify its ability to identify a crack at 50 ft. The inspection system weighs 15-20 lbs and can be transported by 1-2 people from opening to opening. The dimensions are 23 in x 23 in x 4 ft which poses a problem in lowering the camera through the openings. Its 700 horizontal TV line resolution is the best output researched, and the 1000 watt light should provide enough light to illuminate the surface properly. The length of the systems extension can be determined by the inspector. A major limitation of the Mast Grapple system is that it is unable to fit through the cleaning openings.

The Ca-Zoom video system also has potential. The Ca-Zoom video camera is an intrinsically safe 5 in x 2.75 in x 2.75 in video camera. The weight of the camera is 1.5 lbs while the entire system weighs 16 lbs, it has a 8:1 power zoom lens and it is rated to a 100 ft depth in water. The size of the system and the weight allow for the camera to be lowered through the openings and the 8:1 zoom should be able to provide adequate resolution for the inspector.

2.5.3 Climbing Inspectors

Climbing inspectors do not have a comparable basis for the type of inspection that they perform. They were researched based on the time they took for the inspection, the planning days and the manpower necessary for the inspection.

2.5.4 Fiber-Optic Video-Scopes

Fiber-optic video-scopes used in tankship inspections have a small viewing area as compared to the video cameras. The scopes need to be close to the surface to provide a good inspection resolution. To keep the scopes close to the surface for the inspections they could be mounted on magnetic crawlers along with other NDT equipment. The video scope recommended is the Fibercam 500 video-scope. The working length is 50 ft and it has no articulation. The scope is controlled by a CCU and outputs the highest resolution of the scopes researched. The scope has the ability to be mounted with a rotating tip to view the in

plane surface for deformation. The Fibercam 500 with no articulation was chosen over the Welch Allyn Longsteer probes which rely on compressed air. The introduction of an air compressor would provide for more difficulty and weight of the system as well as weight of the tether complicates the system and makes it more cumbersome to transport and operate.

2.5.5 Robotic Arms and Manipulators

Robotic arms researched had been developed for specific purposes. The attributes that could relate to the tankship inspection are the length of the arm, the volume, the weight and the rotation of the arm in the horizontal and the vertical direction. Most of the arms surveyed came from GEC Alsthom. These were designed to function in the nuclear environment and were too heavy and expensive to be useful for tank inspections. The reach length was under 15 ft for all these systems which is less than required. The arm selected for possible inspection uses is the ESM/Titan2 long reach manipulator by Schilling Development. The overall length is 32 ft and it should be able to maneuver through the opening. The problem with all manipulators is the weight and mobility. The weight of the long reach manipulator is 10,400 lbs, and movement by crane would be necessary from opening to opening. A manipulator should be specifically designed for the following considerations: mobility, weight, and length of reach.

2.5.6 Crawlers and Walkers

Crawlers and walkers have been developed for flat plate inspection. The magnetic crawler that has the best probability for further research is the Mark IV-B. The Mark IV is a light weight crawler, under 10 lbs, and has the ability to have equipment mounted on its frame. It can bridge steps of 0.75 inch and can rotate on axis. Problems arise with all crawlers when they are not traveling vertically. The ability for the crawler to cross over longitudinals or to do the inspection from the external shell should be the focus of further research. The crawlers have the ability to carry NDT equipment for testing, and a multitude of tests can be done in one pass of the crawler that could not be done by other inspection techniques.

2.5.7 Thermography

Thermography is a modern idea for use in inspections. The camera's sensitivity and the TV's video resolution should determine the effectiveness of the technique. Weight and spectral range can be important factors and should be tested to determine the feasibility of use in ship inspection. Of the cameras researched, the Tritek 5480 series has a temperature resolution of 0.2 degrees at 25 degree Celsius, outputs a video resolution of 300 TV lines and has the highest benefit to cost rating. The range of these ratings are very close and testing must be done to determine the effectiveness of this inspection technique.

2.5.8 Developmental Techniques

Some of the other techniques described may not be applicable for general inspection but could be utilized in unique situations including evaluating damage. Many are still bench top applications and would require additional effort to be useful commercially..

3 TEST PLAN DEVELOPMENT

3.1 Test Plan Requirements

3.1.1 Statement of Work Requirements

Individual test plans were developed for each separate type of equipment identified in the initial review and prioritization. The primary emphasis was on the equipment's ability to identify flaws or critical areas and to work in areas requiring intrinsically safe or explosion-proof equipment. The test plans were to aid in determining operability, ease of use, and training requirements(Goodwin and Yang, 1994).

The test plans were to list exactly what equipment was being supplied by vendors and what special testing equipment must be supplied by the Government. An overall schedule of tests was also to be included. This latter set of requirements proved to be unworkable because the Government was arranging the tests with the vendors, not the contractor. As a result, the test plan requirements were modified by mutual agreement to those discussed in the following paragraph.

3.1.2 Modified Requirements

As an alternative to separate test plans for each item of equipment, a General Test Plan was prepared that covered all categories of equipment researched and which has applicability to additional equipment types not researched in this study. This General Test Plan provides tests that can be tailored to specific equipments with little or no modification. A separate Specific Test Plan is required for each test which tailors the requirements of the General Test Plan to the needs of the individual equipment. Because the General Test Plan provides test details, the Specific Test Plan can be a short document. Because the Coast Guard Research and Development Center was arranging the test details with the equipment suppliers, they were to develop the Specific Test Plans. However, vendors were often reluctant to share sufficient information about their products. This made it very difficult to plan tests in advance. Also, vendors often waited until the last minute to commit to demonstrating their equipment which made preplanning difficult. In the end, the idea of testing using a test plan was abandoned. In its place, Coast Guard and contractor personnel witnessed demonstrations by the vendors. This less structured approach generally proved sufficient; because, in most cases the equipment was either obviously unsatisfactory for shipboard use or was obviously a useful inspection technique.

A summary of the test plan is included below. Although it wasn't used in this study, it may be useful for future studies.

3.2 General Test Plan

3.2.1 Purpose of the General Test Plan (GTP)

The GTP provides a group of tests applicable to a number of equipment categories that can be referenced in Specific Test Plans (STPs) for equipment. The tests were described in detail to aid in writing STPs for specific pieces of equipment. The tests can be referenced in the STPs by including the test number or by including the full text copied from Appendix A of the GTP.

3.2.2 Test Descriptions and Data Forms

The tests described were intended for tests of the following types of advanced inspection equipment:

1. Remotely controlled lights

2. Remotely controlled video cameras

3. Visual inspection using optical scopes

4. Flat plate inspection using climbers/walkers with NDT instrumentation

5. Flat plate inspection using microwaves

6. Flat plate inspection using acoustic imaging

Many of the tests are general in nature and can be applied to other equipment as well. Some equipment may require additional tests because of its design. These special tests should be included in the STP.

The details of each test are included in Appendix A of the GTP and are not included in this report. A list of the tests included in Appendix A of the GTP is given below.

1. Size
2. Weight
3. Observed Setup Time
4. Observed Break Down Time
5. Inspection Rate
6. Power Requirements
7. Safe for Explosive Atmospheres
8. Observed Personnel Requirements
9. Remote Control Capabilities

10. Subjective Suitability for Proposed Use
11. Detection Resolution
L1. Brightness and Spot Diameter (Lights)
C1. Resolution and Sensitivity (Cameras)
C2. Zoom Capabilities and Field of View (Cameras)
B1. Resolution (Borescopes)
B2. Zoom Capabilities and Field of View (Borescopes)
CW1. Climbing and Instrument Carrying Capabilities (Climbers/Walkers)

These tests form a standard by which different vessel inspection devices can be judged. Because of this, the tests should be conducted without modification whenever possible. The test numbers in Appendix A of the GTP may be referenced in STPs as a full description of the test.

Some tests describe include data forms. A General Data Form was also included which can be used for data collection for tests 1 through 10.

3.2.3 Tests Normally Performed by Equipment Category

The General Test Plan provided the following guidance on tests from the above list that should normally be performed on specific types of equipment.

3.2.3.1 Remotely Controlled Lights

1. Size (Test Number 1)
2. Weight (Test Number 2)
3. Observed Setup Time (Test Number 3)
4. Observed Break Down Time (Test Number 4)
5. Power Requirements (Test Number 6)
6. Safe for Explosive Atmospheres (Test Number 7)
7. Observed Personnel Requirements (Test Number 8)
8. Brightness and Spot Diameter (Test L1)
9. Remote Control Capabilities (Test Number 9)
10. Subjective Suitability for Proposed Use (Test Number 10)

3.2.3.2 Remotely Controlled Video Cameras

1. Size (Test Number 1)
2. Weight (Test Number 2)
3. Observed Setup Time (Test Number 3)
4. Observed Break Down Time (Test Number 4)
5. Inspection Rate (Test Number 5)
6. Power Requirements (Test Number 6)

7. Safe for Explosive Atmospheres (Test Number 7)
8. Observed Personnel Requirements (Test Number 8)
9. Remote Control Capabilities (Test Number 9)
10. Resolution (Test Number C1)
11. Zoom Capabilities and Field of View (Test Number C2)
12. Subjective Suitability for Proposed Use (Test Number 10)

3.2.3.3 Visual inspection using optical scopes

1. Size (Test Number 1)
2. Weight (Test Number 2)
3. Observed Setup Time (Test Number 3)
4. Observed Break Down Time (Test Number 4)
5. Inspection Rate (Test Number 5)
6. Power Requirements (Test Number 6)
7. Safe for Explosive Atmospheres (Test Number 7)
8. Observed Personnel Requirements (Test Number 8)
9. Resolution (Test Number B1)
10. Zoom Capabilities and Field of View (Test Number B2)
11. Subjective Suitability for Proposed Use (Test Number 10)

3.2.3.4 Flat plate inspection using climbers/walkers with NDT instrumentation

1. Size (Test Number 1)
2. Weight (Test Number 2)
3. Observed Setup Time (Test Number 3)
4. Observed Break Down Time (Test Number 4)
5. Inspection Rate (Test Number 5)
6. Power Requirements (Test Number 6)
7. Safe for Explosive Atmospheres (Test Number 7)
8. Observed Personnel Requirements (Test Number 8)
9. Remote Control Capabilities (Test Number 9)
10. Subjective Suitability for Proposed Use (Test Number 10)
11. Climbing and Instrument Carrying Capabilities (Test Number CW1)

3.2.3.5 Flat plate inspection using microwaves

1. Size (Test Number 1)
2. Weight (Test Number 2)
3. Observed Setup Time (Test Number 3)
4. Observed Break Down Time (Test Number 4)
5. Inspection Rate (Test Number 5)
6. Power Requirements (Test Number 6)

7. Safe for Explosive Atmospheres (Test Number 7)
8. Observed Personnel Requirements (Test Number 8)

9. Detection Resolution (Test Number 11)
10. Subjective Suitability for Proposed Use (Test Number 10)

3.2.3.6 Flat plate inspection using acoustic imaging

1. Size (Test Number 1)
2. Weight (Test Number 2)
3. Observed Setup Time (Test Number 3)
4. Observed Break Down Time (Test Number 4)
5. Inspection Rate (Test Number 5)
6. Power Requirements (Test Number 6)
7. Safe for Explosive Atmospheres (Test Number 7)
8. Observed Personnel Requirements (Test Number 8)
9. Detection Resolution (Test Number 11)
10. Subjective Suitability for Proposed Use (Test Number 10)

3.3 Specific Test Plans

The General Test Plan provided the following guidance concerning the contents of Specific Test Plans.

3.3.1 Purpose of Specific Test Plans

The Specific Test Plans provide the details for an actual test. The GTP provides tests that can be applied to a particular type of equipment but the STP must tailor these tests to apply to a particular device. Details, such as tests to be performed, location, time, participants, and documentation required, are to be included in the STP. The GTP may be referenced for details of individual tests and is intended to be a shopping list for tests when preparing the STPs. The STP will be the governing document in determining how testing will be conducted.

3.3.2 Content of Specific Test Plans

Specific Test Plans should be organized into the sections given below. Required items for each section have been listed. Additional information may be included as the author of the STP sees fit.

a. Introduction

1. Purpose of the Test - What equipment is being tested and for what purpose?

2. Background - Give administrative information explaining why your organization is conducting these tests. A brief explanation of how the equipment was obtained for testing should also be included.

3. Objectives - What are the objectives to be accomplished by conducting these tests? Be specific. A test must be included in the STP to address each of the objectives. Conversely, tests should not be included if they do not satisfy one of the objectives stated.

4. Scope of the Tests - Where will the tests be conducted and for how long? Reference other documents which cover the tests such as OPORDERS and test plans for concurrent tests, if any.

5. Schedule of Events - All significant events should be included in this schedule. As a minimum, the schedule is to include the period beginning with STP preparation and ending with the test report submittal.

b. Organization

1. Participants - List the commands and individuals involved with the tests and the name and phone number of contacts.

2. Responsibilities of Participants - The responsibilities of each of the participants are to be detailed in this section.

c. Testing

1. Test Descriptions - This section should contain a listing of all tests to be performed together with a reference to where the details of the test may be found. This may be a reference to a test in this GTP. Tests not included in this GTP should be described in detail and included as an appendix to the STP. Any changes to the test descriptions should be detailed in this section.

2. Priority of Tests - Order the tests according to priority. Testing will be conducted according to this priority when possible. This will help ensure that the most important tests get accomplished even if a mechanical breakdown or other problem forces an early termination of the testing.

3. Concurrent Tests - List any testing not included in the STP which will be occurring during the time frame of the tests covered by the STP.

d. Documentation

1. Photography - Prescribe the minimum amount of photographic coverage which will satisfy the test objectives. Photographic requirements are listed with the tests in this GTP and should be provided for unique tests included in the STP. Modifications to the photographic coverage listed for test in the GTP should be described in the STP.

2. Handling of Data Sheets - Describe the procedures to be followed in preparing and handling data sheets to ensure that all data collection forms are completed and returned to the test director.

3. Test Reports - Give the details of what test reports will be provided and when. This GTP prescribes the method for analyzing data from each test. Any deviation from these methods should be included in this section of the STP.

4. Test Director's Journal - The test director should be required to maintain a journal listing all significant events which occur during the planning and conduct of the tests and data analysis. This journal is intended to provide a chronologic record for reference by the report writer or by a substitute test director, should a substitute be necessary.

4 EQUIPMENT AND TECHNIQUES DEMONSTRATIONS

4.1 Introduction

4.1.1 Demonstrations Rather Than Tests

As previously mentioned, the planned controlled testing using test plans had to be abandoned because of the difficulty in getting commitments and information from vendors. Instead, a series of equipment demonstrations were held that provided a great deal of information and allowed conclusions to be drawn concerning the equipments usefulness for shipboard inspections. This chapter discusses the findings of these demonstrations.

4.1.2 Details of Demonstration Participants, Times and Locations

Demonstrations were conducted at the Coast Guard Research and Development Center, at the plant of ROV Technologies in Vermont, and on board the ex-USS Milwaukee at the Philadelphia Navy Yard. The first demonstration took place in early December 1994 when Valtec Systems, Inc., of Beverly, Massachusetts, presented a demonstration of four of Welch Allyn's flexible borescope products at the Coast Guard R&D Center. Later in the month, Olympus America, Inc., provided a demonstration of several of their products at the R&D Center. In January, Kurt Hansen of the R&D Center and Mike Goodwin of MAR, Inc., visited the factory of ROV Technologies to view several of the companies inspection products under construction.

The shipboard demonstrations were scheduled during two periods, the first from January 23 - 27, 1995, and the second from February 27 to March 3, 1995. Both sets of demonstrations were held at the Philadelphia Navy Yard. Most of the equipment demonstrations took place on board the ex-USS Milwaukee (AOR-2) in a forward tank (6-25½-0-V). This tank was a void that had previously been a fresh water tank. The demonstration of the MARICAM 2 system from Northeast Technical Services took place in a warehouse on the Navy Base. The magnetic crawler from NDT Technologies was demonstrated in the dry cargo spaces on the Milwaukee. Coast Guard Marine Inspectors from the Marine Safety Office in Philadelphia were present for all demonstrations.

4.2 Remotely Controlled Lights

Only one remotely controlled light was demonstrated. A Guest Beamer remote control spotlight was lowered into the void and used during both periods to support other demonstrations. The spotlight was mounted to a base made of two crossed 2 x 4 's, each about 3 feet in length. The light stood on a pipe pedestal about 24 inches above the center of this base. The 12 VDC light was wired to an AC to DC converter and power was supplied via an AC power cord from the top of the trunk to the tank. The size of the base made it awkward to handle, particularly when transitting doors and passing the light down the hatch.

However, the crossed 2 x 4's provided a very stable base once the light was in the tank. The spotlight had radio-controlled rotation and elevation as well as a remote on-off feature. The light rotates through 180 degrees to each side of the mid point but can not continuously rotate. There was about 45 degrees of vertical rotation above and below horizontal. The radio control is a small box about 3" square by 1" thick that easily fits into a coverall pocket. The control is easily operated even with heavy gloves on. All in all, this light did a good job of illuminating the tank for our purposes. It was easy to direct to areas for photography purposes. The base was put together by the R&D Center for test purposes. With some redesign, including a folding tripod base and an integrated AC-DC converter, this type of light could be very useful for inspection purposes. It must be used only in spaces that are safe for hot work.

4.3 Video Cameras

No video camera was demonstrated as a separate entity. However, several were demonstrated as part of other systems. The Visual Inspection Technologies' magnetic crawler had an onboard camera and lighting system when was connected via an umbilical to a monitor outside the tank. This camera provided a black and white image. It could be panned and tilted relative to the crawler.

The EM&I Marine climbers had a helmet mounted color video camera connected to a monitor on deck. The climber also had a headset and microphone to talk with personnel on deck. The deck-based personnel can direct the climber to show them areas of interest which the climber does by looking at the area. The EM&I Marine system used a low light level camera which relied on the climbers headlamp for illumination.

The MARICAM 2 system incorporated a black and white camera and a deck-based monitor, as well. This camera is paired with a powerful light and a 20X zoom lens to allow "close-up" viewing of objects up to 50 feet from the camera. The camera can be tilted vertically and panned by rotating the support structure.

Vendors discussed the trade off between black and white and color cameras. While color gives a more natural appearance and allows such things as rust to stand out, the resolution of color cameras is not as good as that of black and white cameras. Also, in low light situations, the color tends to look faded. Companies that use black and white systems stated that inspectors quickly learn to identify defective areas on the black and white display with as good or better accuracy. The higher resolution is believed to be more benefit than the loss of color.

4.4 Climbing Inspectors

The inspection services provided by EM&I Marine to inspect ships using climbing techniques were demonstrated during the second Philadelphia trip. EM&I Marine is a British

company that has used climbers for many years to inspect oil platforms in the North Sea. Several years ago they expanded their inspection services to include tankers and bulk carriers. The company offers survey services and also painting and welding services. Their survey services go by the acronym MASS which stand for Marine Access Survey and Safety.

MASS surveys are carried out either at sea or in port in tanks that are safe for human entry. The surveyors carry gas sensors and leave a tank immediately if a unsafe atmospheric condition is detected. The survey is performed by highly trained climbers who are proficient in the climbing techniques used by cavers and mountain climbers. The surveyors are also trained in visual and ultrasonic inspection techniques. First, a senior member of the climbing team, one with at least 2,000 hours of climbing experience, enters the tank and rigs lines as needed to the overhead. Then, survey specialists enter the tank and use the rigged lines to access the areas to be inspected. The survey specialist carries a helmet mounted, color video camera which feeds an on-deck monitor. A separate black and white camera is set up in the tank to provide a location view to assist on-deck personnel in establishing the surveyor specialist's location in the tank. The survey specialist also has earphones and a boom microphone to talk with people at the monitor station. The intent is for class society surveyors or owners representatives to view the inspection on the monitors while talking to the in-tank survey specialist and directing his movements. Essentially the people on deck have a very intelligent robot feeding information back to them. The in-tank survey specialists can perform as directed but can also point out defects not seen by the personnel on deck.

In addition to providing video images, the in-tank survey specialist can take ultrasonic measurements. The company emphasizes preplanning of ultrasonic surveys and assists owners to plan such surveys. Having a trained inspector up close allows the company to report on the general condition of structure which greatly enhances the ultrasonic data collected.

The climbers can rig a powered basket hoist called POWERMAP to allow close up access by surveyors who can't get to the area on ropes. This also allows welding, blasting, and painting work to be performed.

The MASS system has been approved by major classification societies including Lloyds' Register, American Bureau of Shipping, Nippon Kaiji Kyokai, and Det Norske Veritas. The company provided documentation of 26 ships that have been inspected including 8 VLCCs.

Because the company has to rig lines for inspection access, a natural extension to their services was performing painting and repair work while these lines are still rigged. They call this service C-FIX - "See It - Fix It." The POWERMAP basket lift allows them to perform high pressure water blasting, grit blasting, coating maintenance, and pipe work and structural repairs.

Although these services seem manpower intensive, the company claims survey costs using MASS are less than half the costs for similar surveys using rafting or staging. A better inspection can be performed using MASS also.

An initial presentation was conducted in a conference room with several senior ABS representatives and one HESS Oil Company representative present. The safety aspects of the climbing operation were emphasized. With the attention paid to backup systems, it appears that climbing is actually safer than rafting or staging. The principals discussed in the conference room were demonstrated the following day on the ex-USS Milwaukee.

A senior rigger and a survey specialist demonstrated the MASS technique. Lines were rigged to the otherwise inaccessible port side of the tank used for previous demonstrations. A close up inspection near the overhead was performed. ABS's senior surveyor from the New York office and a HESS Oil representative viewed the inspection on monitors and directed the inspection technician in the tank. Although this was not a particularly difficult tank to rig, the team was able to demonstrate the ease with which a tank can be rigged for climbing. They also demonstrated techniques for moving around in a tank.

The deck-based surveyors quickly adjusted to directing the survey specialist via headset. They commented that this method would be an effective method to use during an actual survey.

4.5 Fiber-Optic Video Scopes

Video scopes were demonstrated in a laboratory situation and also on board ship in the engine and fire rooms. Several systems from Welch Allyn and Olympus America were demonstrated. All these work very well for close-up viewing of small areas and might have some applicability for viewing local areas behind inaccessible stiffeners or the insides of tubes. None worked very well for viewing surfaces at 18 inches or more from the probe tip. The lighting supplied by the fiber optics was the major factor in this. Both companies have larger size systems with probes of 0.5 inch diameter or more. They claim these systems provide sufficient light to view objects up to two feet away. Such systems were not demonstrated, however. If video scopes are to be useful for inspecting boiler drums or air flasks, a viewing distance of at least two feet is essential. The larger, heavier video scopes will be more of a problem to move around in the ship. The larger systems demonstrated were already difficult to transport easily.

Video scopes do give an excellent display of objects within their field of view. It is likely that the larger systems would do even better. One other problem with video probes is the difficulty with orientation of the probe to the object being viewed. Unless some landmark on the object is visible it is easy to lose track of where you are. You may find defects but not know where they are located.

Figure 8 Welch Allyn Video Probe XL

Locations in the fire room and engine room were used to conduct a demonstration of the Welch Allen Video Probe XL, Figure 8, scope first demonstrated at the Coast Guard R&D Center. This scope was lowered into the test void but proved to be totally ineffective for use in a large space. Several locations in the fire room were inspected including the mud drum of one main boiler, a burner opening, and a main feed pump discharge line. Several other interesting locations in the fire room and engine room were located but a working electrical outlet was not available in the vicinity to plug in the scope.

The main boiler mud drum was inspected first. This was a pressure vessel about 15 to 20 feet long and about 2 feet in diameter. The borescope tube lay on the bottom of the drum. An attempt was made to view the tube inlets on the top of the drum but the borescope did not put out sufficient light to see the tubes clearly (about 2 feet away). Next, the borescope was inserted into the boiler casing through a burner tube. The inside of the tube was easily inspected but the inside of the boiler was not visible using the scope. Even inspecting the area around the burner by turning the tip of the scope 180 degrees proved ineffective. The borescope was then inserted into the outlet pipe of one of the main feed pumps where a check valve had been removed. The probe was used to inspect a location was about 7 feet and several bends away from the pipe opening. The scope was snaked into the 4 inch pipe and gave good views of the erosion of the pipe and the pump outlet. It was then passed into the other half of the open pipe and gave good views of the insides of an open gate valve. The AC powered unit was cumbersome to pack around especially up and down ladders. Also, working AC outlets were in short supply in the fire room and nonexistent in the engine room. The battery powered unit would have been better for the application.

Two Olympus borescopes were also demonstrated, a larger one 12 mm in diameter and a smaller one 6 mm in diameter. The larger scope was used to look inside the boiler mud drum and inside the side wall header of the boiler casing. The smaller one was used in the engine room to look inside the tubes of a cooling condenser on one of the reefer compressors. It was also used to look at the underside of the pistons on the same compressor. The smaller borescope did a good job in the reefer unit inspections. This was the type of work it was designed for. However, the larger unit faired no better than the Welch Allen unit in the boiler drum inspection. It could not see across the diameter of the drum. It did a good job inspecting the header which was about 6 to 8 inches in diameter. Both of the units demonstrated were far less portable than the Welch Allen unit. Inspectors did like the video display features of both companies' units and the freeze frame feature of the larger Olympus borescope. One inspector stressed the need to measure the depth of pitting.

4.6 Robotic Arms and Manipulators

Nothing that could be classed as a robotic arm or manipulator was demonstrated. The closest device was the MARICAM 2 system which maneuvers a camera and light from a single vertical support.

The MARICAM 2 system from Northeast Technical Services is designed to extend into a tank through a manual Butterworth opening, approximately 12.5 inches in diameter. The camera is about 11 feet below the top of the tank. This made it unusable in the long trunk of the tank on the ex-USS Milwaukee. As an alternative, the system was assembled and demonstrated while laying flat on the warehouse floor. This worked as well as an in-tank demonstration.

The main use for the MARICAM system is inspection of under deck structure. The camera system consists of a camera and light attached to a vertical rod which is supported by the Butterworth opening. The support plate fits over 3 studs on the Butterworth opening. The vertical support rod swivels in a bearing on this plate allowing the camera to be swivelled 180 degrees to either side of the mid position. The camera and lens assembly is mounted to the bottom of the vertical support rod and swivels vertically from about 30 degrees below horizontal to near vertical. A 1,000,000 candlepower, Collins Dynamics light is mounted 3 to 4 feet above the camera and swivels up and down with it. However, a separate adjustment allows the light to be moved away from the camera viewing area if less light is needed. The light has a spot and a flood setting. The flood setting is used for near field work while the spot setting is used when the inspection area is far away. The camera and light vertical angle is adjusted by a handwheel at the top of the support rod. A smaller handwheel allows separate adjustment of the light position. Two tee handles on the top of the support rod allow the rod to be swivelled. A cam lock is provided to lock the rod in any desired horizontal position.

The camera has a remotely controlled power zoom lens with a maximum enlargement of 20X. It is designed to inspect structure up to 50 feet away. The demonstration clearly

showed that it was capable of such an inspection. The camera provides a black and white image on an above deck monitor. Two operators are required. One operator controls the camera zoom and focus and looks for defects. The other operator watches over the shoulder of the first operator and repositions the camera and light as necessary.

The whole unit is designed for set up and movement between tanks by two people. Besides the camera support rod, which weighs about 90 pounds, there is a monitor/control box, estimated weight 50 pounds. The control box is disconnected each time the camera is moved to a new deck opening. Moving between tanks takes about 5 minutes. Setup time out of the shipping box was less than 30 minutes as was the repacking time. All components were designed for work on a tanker's deck in all weather conditions. Survey work is stopped only in case of heavy rain. The control station was designed to shield the monitor for viewing in strong light conditions. The system is designed for use in a tank that is safe for hot work. The light is the primary danger. A third recording module is also shipped with the unit. Video recording is usually done only when suspected problem areas are found. The system included a titler to add text to the recorded images.

When packed, the system consists of two heavy boxes which have to be lifted on board by a crane. All remaining work can be done by the two man team without outside assistance. Electric service, 115 VAC, is required. Spares are carried in the shipping boxes along with electrical extension cords.

A simple inspection device was viewed during the visit to ROV Technologies that could be placed in this category. This consisted of an extendable rod, such as used by painters, to which a small video camera and two lights were mounted. See the Figures 9 and 10 below. The inspector has a vest with a fold down monitor and belt mounted batteries. A practical maximum length for the rod is about 20 feet. Such a device allows close-up viewing of may places that would otherwise be unaccessible. In a small vessel it might permit a more complete inspection of spaces.

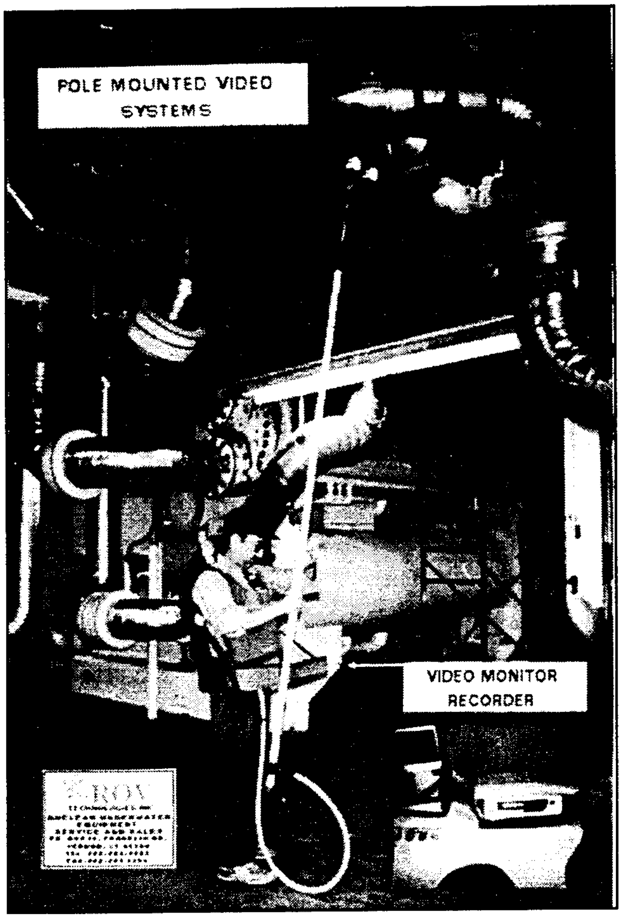

Figure 9 Video Extension Rod

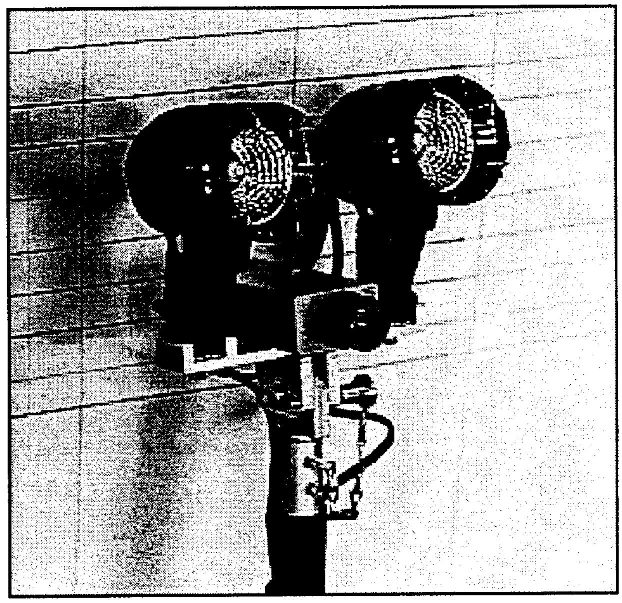

Figure 10 Close-up of Camera Head

4.7 Crawlers and Walkers

Two magnetic crawlers were demonstrated on board the ex-USS Milwaukee. Another was viewed and discussed during a tour of the ROV Technologies factory in Vermont. A completed unit was not available for demonstration but a nearly complete crawler was available for viewing the internal parts. The two crawlers demonstrated included one from Visual Inspection Technologies and one from NDT Technologies. These two demonstrations are described further below.

The Visual Inspection Technologies (VIT) remotely-controlled crawler consisted of several small electronic modules and a crawler with four magnetic wheels which mounted a video camera. The crawler was tethered to the top of the tank by several cables carrying electric power, control signals and the camera video signals. The camera could pan and tilt remotely and the four magnetic wheels of the crawler could be operated independently to allow the crawler to go ahead or backwards and to turn the platform. The crawler was designed for going through low areas and had about 1" of ground clearance. This proved to be a problem

in several cases when passing over structural discontinuities but could be corrected by increasing the ground clearance for the Coast Guard application. The crawler was about 12 inches wide by 18 inches long. With its magnetic wheels it could run on vertical steel plates and also along the tank overhead. The camera had its own lights and could give a close up view of structure near the crawler.

The crawler performed well but has several drawbacks. The previously mentioned low ground clearance is one problem. The crawler was run down the side of the trunk. At each deck level there was a ridge about 1 inch high. The crawler had difficulty when its body struck the ridge. A distance measuring transducer on the crawler had a low casing that also got stuck on the ridges. The wheels had no difficulty rolling over the ridges going down. However, after going down and operating for a while on the overhead, the wheels picked up quite a bit of iron and rust particles which are normally scraped off by scrapers above each wheel. One of these scrapers had excess clearance and a small washer became jammed beneath the scraper. This made it difficult for the wheel to turn. On the way up the crawler lost its hold on the trunk wall and fell off, possibly due to the effect of the rust particles and jammed wheel.

Where the overhead was clear and the coating was sound, the crawler had no trouble navigating on the overhead, even over shallow welds. However, when the crawler was maneuvered over an area which had a concealed rust layer (scale) under the coating, the crawler lost its grip and fell from the overhead, damaging one of the cameras lights. It is interesting to note that the operator could not tell from viewing the monitor that there was rust present that could cause the crawler to lose its grip.

The crawler and its electronics took less than 15 minutes to set up and to break down. Except for the problems mentioned, the system worked very well. However, its operation is limited to flat plates with only small obstructions and no loose rust.

The NDT Technologies crawler demonstrated was slightly smaller than the VIT crawler but had similar features. It was designed to carry an ultrasonic transducer and did not have a video camera. It was able to climb on a vertical surface and run upside down on the overhead. It was not run over rust but likely would not hang on if the surface is rusty. A small washer was placed under one wheel which did not inhibit the climbing ability significantly. Since this unit didn't have a camera system the control unit was a box about 12 inches square and 2 inches thick. The ultrasonic unit requires a similar sized box plus some form of recorder such as a chart recorder. A gallon of fluid is also needed to provide and interface between the transducer and the metal surface. The crawler generally performed well but was hard to turn and the knurled wheels scraped quite a bit of paint from the surface. In a rusty environment the rust would be scraped off and stick to the wheels, possibly impairing traction or holding power.

4.8 Polarized Light Visual Enhancement

A polarized light system developed by Dr. Lawrence Wolff of Johns Hopkins University was experimented with during both Philadelphia visits. The polarized light system consisted of a liquid crystal lens unit that was mounted in front of the lens of a Sony Camcorder. This unit rapidly rotated the polarization angle of the lens through horizontal, vertical and 45 degrees using electronics. Three images are obtained, one for each polarization angle. These three images can be compared for intensity. The ratio between the minimum and maximum intensity at the three polarization angles can be compared to determine areas having different characteristics. The hope is that rust versus sound coating can be discerned and that cracks might be made to stand out more.

The camera was set up in the tank on a tripod and several interesting areas in the tank were video taped. These were be taken back to John Hopkins University for analysis at the end of the first visit.

During the second visit, Dr. Wolff demonstrated a set of polarized goggles he had developed using the techniques demonstrated previously. Computer enhanced pictures from the prior demonstration were also shown and discussed. It did not appear that the polarized light camera system was able to detect anything that wasn't obvious to an observer in regular light. The goggle system did not work well. It was no easier to detect rust or other defects with the goggles on than with them off. Also, the goggles have an annoying flicker. Dr. Wolff has prepared a report on his work which is included as Appendix A of this report. The report is titled "Polarization Vision Study for Ship Tank Inspection."

However, the system may be useful to detect the presence of oil on water. There seems to be a color shift towards red for light reflecting off oil as opposed to water. This may be useful to detect and track oil spills from an aircraft, particularly if the color shift can be enhanced. Further testing of this might be beneficial.

4.9 Summary and Conclusions Based on Demonstrations

4.9.1 Promising Equipment and Techniques

The most promising devices or techniques demonstrated are already being used for marine inspections. Both deserve consideration when conducting tankship surveys. Also, the radio controlled spotlight used proved to be quite useful for general illumination of a tank during an inspection provided AC power is available and can be safely used.

The climbing techniques and equipment demonstrated by the British company EM&I Marine appear to be cost effective and safe. A senior surveyor from ABS and a senior oil company representative participated in a mock survey and found that they could easily direct the in tank survey specialist to provide them with an up-close video image as well as a trained

human assessment of local structural conditions. This is something no robotic system can provide. Based on the vendors cost estimates, the approach appears to be very cost effective when compared to rafting or staging for an equivalent level of inspection. It is the only technique reviewed where ship size is not a limiting factor. The principal limitation of the system is that tanks have to safe for human occupation before the inspection takes place. However, the same limitation applies to rafting or staged inspections. This technique can be used for inspections at sea with greater safety than rafting.

The second promising device was Northeast Technical Services MARICAM system. A great deal of thought had clearly been given to making this system usable aboard ship. The system works well for its intended purpose which is limited to overhead structural inspections and inspections of upper bulkhead structure. Much thought was given to packing the system in compact units that are relatively easy to transport. Also, a full set of spare parts is packed with the unit. The system was designed for an independent two man team to operate and transport it from tank opening to tank opening. The camera with its zoom lens and associated powerful light made it possible to inspect structure up to 50 feet away and still detect small cracks. The primary limitation is that much of the structure may be blocked from view by other structure. However, the system permits a much better inspection of tank overheads, at a much lower cost, than is currently available by any method except full tank staging.

4.9.2 Equipment and Techniques That Didn't Work Well

In the limited tests/demonstrations performed, it was not obvious that any of the remaining techniques offer an improvement over current practice. Tests of the laser non-contact ultrasonic holds promise and the results will be reported by the end of 1995. Video cameras in general hold promise when properly incorporated and used. This was evident in both systems recommended above. They must be selected for a specific use and viewing range to be effective. Fiber-optic video scopes were a disappointment but the vendors' claim not to have demonstrated their most powerful models which would have been effective in shipboard applications. Crawlers have very limited applicability to shipboard inspections and clearly don't cling to the surface well when rust is present, as it usually is. The polarized light enhancement system showed little improvement over viewing in unpolarized light.

5 CONCLUSIONS AND RECOMMENDATIONS

5.1 Methods for Improving Up-Close Visibility

Two good general methods for improving up-close visibility were found in this study. One, the use of climbers with survey training, is really only a better way to get the survey specialist close to the area being inspected. The second method requires the use of video cameras with a telephoto lens and sufficient lighting to illuminate the area being inspected. This method works better than expected for viewing the part of the structure the camera can see. There is much of the structure that is blocked from view by adjoining structure. Use of a lightweight camera and lighting together with a manipulator arm that can be inserted into a tank cleaning opening offers promise.

5.2 Use of Remote Video

Use of remote video for inspections came out better than expected during shipboard demonstrations. There was concern that the inspector would lose interest in watching the monitor for extended periods and hence miss important structural failures. This may be the case for a camera that is scanned under automatic control (not controlled by the inspector). However, when the inspector has control over the camera, we observed no loss of concentration. The use of climbers with helmet-mounted video cameras was a particularly good application of video. Here, the on-deck inspector can direct the in-tank survey specialist to show him details while the survey specialist describes local conditions. This interactive feedback provides a much better level of inspection.

The video system demonstrated all require tanks to be safe for hot work. This is due primarily to the explosion hazard caused by associated lighting systems. The cameras and lights can be made very small and light, VIT has a camera and lights weighing 1.5 lbs. This permits video systems to be mounted on lightweight booms, but the explosion hazard is still present from the lights.

One area that should be research further is the use of a fiber-optic video scope in conjunction with a manipulator boom. A high powered fiber optic system would be needed to allow objects from 6 inches to at least 3 feet away to be viewed clearly. The camera head should be mounted to the end of the manipulator boom so that remote movement of the camera head, either by a wire or air pressure system, produces a known orientation of the camera to the end of the arm. A system such as this would have the major advantage that the tank would not need to be gas freed before use. The monitor and light source could be on deck with the manipulator arm suspended from a tank cleaning opening similar to the MARICAM system. Consideration would have to be given to preventing explosions of vented vapors above deck. There would be nothing in the tank itself that could cause an explosion. The demonstrations of video scopes clearly indicated that their pictures are as good as any other video cameras despite their small size. A horizontal manipulator arm of at least 30 feet in length would be

needed to reach areas between cleaning openings. The only weight the arm would have to carry is the distributed weight of the fiber optic probe.

5.3 Developmental Techniques

Except for polarized light techniques, which showed little promise in shipboard experiments, none of the developmental technologies was demonstrated. Little more can be said about these technologies than has been reported in Section 2 of this report. None of these appear to be superior to current inspection methods. The non-contact laser ultrasonics tests will occur in the summer of 1995.

5.4 Techniques Not Evaluated

There are ongoing efforts throughout the maritime and other industries that were not evaluated due to schedule, cost and time constraints. Some information appeared in literature and for others, details were accumulated through telephone calls and facility visits. Many of them are associated with U.S. Navy efforts and the MARITECH Technology Program out of the Advanced Research Projects Agency (ARPA). The efforts are briefly described below so that marine inspectors, classification societies and Coast Guard inspectors know what may be seen in store for the future.

5.4.1 Underwater Vessel Inspections

There are ongoing efforts in the area of evaluating the ship structural integrity from under the water. The U.S. Navy is funding multiple tasks in several areas in order to determine the condition of their vessels before entering a drydock. These efforts include weld quality, plate thickness and magnetic particle methods. Qualification procedures for underwater welds and the magnetic particle efforts are centered at the Coastal Systems Station of the Naval Surface Warfare Center (NSWC) in Panama City, Florida (Mittleman and Swan, 1993). The development of an automated underwater hull maintenance vehicle is occurring at the Annapolis Detachment of the Carderock Division of NSWC (Bohlander, et. al.,1992). Use of an acoustic navigation system permits a diver or vehicle to collect data and have it automatically mapped to the ship's hull. A company in Great Britain, IKU, has already developed a system which can measure and provide a color chart showing hull plate thicknesses. An inspection of a VLCC can be performed in less than 24 hours (IKU, 1994).

5.4.2 Automated Weld Evaluation

The Navy has also sponsored research in automated welding and weld evaluation. One activity performing research which was previously described is the Navy Joining Center (NJC) operated by the Edison Welding Institute. The NJC is performing research in many areas, among them are the laser inspection system previously described and the Programmable Automated Welding System (PAWS) which monitors the weld quality as the weld is done. The

Annapolis Detachment of NSWC has focused research to find technology which could replace x-ray radiography with ultrasonics within the submarine fabrication program, and utilizing lasers and ultrasonics for pipe thickness. The Naval Ship Systems Engineering Station (NAVSES) in Philadelphia is also evaluating advanced techniques for use in inspections. This has included the use of Laser Optic Tube Inspection System (LOTIS) which can profile the internal surfaces of piping, especially for sections which cannot be accessed from the outside.

5.4.3 Double Hull Technology

The Navy is also sponsoring research centered at the Carderock Division (NSWC) in the area of advanced double hulls for combatants which may also be applicable to the commercial shipbuilding business. The Advanced Double-Hull Technical Symposium in October, 1994, addressed design and maintenance (inspection and repair) issues of the new design and a prototype Remote Maintenance Vehicle described there may have additional applications in other vessel designs.

5.4.4 MARITECH Program

The Advanced Research Projects Agency (ARPA) is sponsoring much research in the area of shipbuilding, especially in the areas of promoting newer technologies such as robotics. The program is encouraging the development of new technology and applications in the areas of vessel design and fabrication. All of the projects are trying to identify technologies which can make the US shipbuilders more competitive in the world economy. Among the project that address technology directly are:

- Portable Shipboard Robotics - with CYBO Robots, Inc heading the list of companies that are participating.
- Design of the Virtual Reality Shipyard - US Shipbuilding Consortium
- Integration of the Modern Manufacturing Methods and Modern Information Systems - with Todd Pacific Shipyard as the leader.

The same hardware and software used in the design and manufacturing processes may be used in the future to control a camera with an ultrasonic gauge on the end.

5.4.5 Structural Sensing

Many methods of in-situ structural monitoring have been attempted by several companies including vibration monitoring and acoustic emission. The cost required for the thousands of sensors required for each ship is one of the primary stumbling blocks. The increase of computer capacity along with new lightweight and cost effective sensors may make these methods more feasible in the future. One example is the use of fiber-optic sensors by the Optical Sciences Division of Naval Research Laboratory (NRL) in Washington as mentioned in a recent Maritime Reporter. The result would be a lower cost per channel.

5.4.6 Other Industries

There are other industries which are attempting to increase the use of technology in increase the effectiveness and safety of inspections. The highway bridge is utilizing trucks such as the SONSUB boom equipment and the California Department of Transportation is using a small radio controlled small helicopter. The nuclear industry is also developing new robotics systems to monitor nuclear waste sights. One company, SPAR Aerospace, Limited of Canada (company who built the space shuttle arm) has modified the software and hardware to include a structural avoidence method which we greatly reduce the chance of damaging the arm in a nuclear storage facility.

Two major symposia have address nondestructive issues just this year. The Energy and Environmental Expo "95, in Houston in January, had a Nondestructive Symposia in which papers from the transportation, energy and maritime industries participated. The International Society for Optical Engineering held a large conference in June in California and again representatives from all industries participated including aerospace, railroads and civil engineering issues such as tunnels and bridges were addressed. The proceedings were not available at the tine that this report was written.

6.0 FINAL RECOMMENDATIONS

Most of the advanced technologies being evaluated in this report are not the type of methods that would be used directly by Coast Guard inspectors and are also beyond the scope of the inspection program's budget. But the commercially available methods such as the climbing inspectors, remote video cameras, and the advanced fiber optic borescopes, will permit marine inspectors to access areas not seen previously and the maritime industry should be encouraged to utilize them and develop them further. The ultimate goal is to develop techniques which will permit inspectors to remain outside cargo and ballast tanks to increase safety and efficiency. Vessel owners and operators will be the beneficiaries although some of the scanning methods may be useful to the Coast Guard for performing quick evaluations of foreign vessels offshore as the techniques are refined and commercialized. The Coast Guard and classification societies must keep up-to-date with the latest design and fabrication processes being developed. Many of the problems encountered in other industries are similar and cooperation will result in safer and more efficient inspections by all parties.Technology is advancing so rapidly that the Coast Guard should consider reviewing inspection techniques every 3-5 years, especially as the ongoing Navy and MARITECH projects are completed, in order to encourage the maritime industry to keep pace. Finally, as the technology advances, Coast Guard inspectors should utilize technology when available and policies and procedures reviewed periodically to reflect the changing environment.

7.0 REFERENCES

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APPENDIX A

POLARIZATION VISION STUDY FOR SHIP TANK INSPECTION

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This report summarizes a study for assessing the use of Polarization Vision Technology for inspecting damage to ship storage tanks. Experimental results are shown particularly for identification of cracks and protrusions due to rust. Recommendations are made as to what circumstances polarization vision technology may be advantageous to enhancing inspection capability, based upon experimental results.

PROJECT SUMMARY

On January 24, 1995 and March 1, 1995 various portions of an empty water storage tank aboard the U.S.S. Milwaukee in dock in the Naval Ship Yard at Philadelphia was filmed using a Polarization Camera Sensor. The Polarization Camera Sensor was constructed using a top of the line Sony TR-500 Hi-8 video Camcorder together with a liquid crystal optical head mounted in front of the Camcorder lens, and an electronic box to drive the liquid crystals in synchronization with the Camcorder video rate. The liquid crystal optical head enabled the resolution of three different orientations of polarization at 0^o, 45^o, and, 90^o in sequence. For a more detailed description of the Polarization Camera Sensor that was used see the article, "Advances in Polarization Vision" by L.B. Wolff in the Proceedings of the ARPA Image Understanding Workshop, November 1994 (this article also includes results from a previous U.S. Coast Guard sponsored study at the Naval Surface Warfare Center, Annapolis Maryland studying ship hull damage utilizing a similar Polarization Camera Sensor). The Hi-8 Camcorder, which weighs about two pounds and can be easily held with a single hand, was mounted on a tripod for stability within the empty ship tank, and Hi-8 video tape within the Camcorder recorded polarization component image sequences at 15 polarization components a second (i.e., each component at 0^o, 45^o, and 90^o was recorded every 1/15

second). Various portions of the inside of the empty ship tank were polarization recorded onto video tape under different illumination conditions and different viewing angles. Linear polarizing material was placed in front of the illuminating light source. The Hi-8 video cassettes containing the recorded polarization component images were then brought back to Baltimore for computational processing and analysis for automated detection of damage.

Also experimented with on March 1, 1995 were Polarization Goggles that could be placed over the face with a liquid crystal optical head mounted in front of each eye. The small switching box for the liquid crystals is held in the palm of a hand enabling the inspector to vary the speed at which the liquid crystals switch. The Polarization Goggles effectively give a direct view to the inspector of the same temporal polarization component image sequence sensed by the Hi-8 camcorder. The psychophysical effect is that where there is the presence of linear polarization in a scene there is a lighter-darker "scintillation" as the crystals switch between the 0^o, 45^o, and 90^o states, the difference between lightest and darkest being more dramatic with a stronger presence of linear polarization- unpolarized light does not "scintillate" at all. The Polarization Goggles can be switched off altogether giving the inspector a standard intensity view if desired, so in effect these goggles do not impede normal viewing. The inspector can use an illuminating light source either mounted on a helmet, or held in his/her other hand.

RESULTS

What appeared to be the most significant feature of the polarization component sequences recorded onto the Hi-8 video tape brought back to Baltimore for processing was the ratio of the maximum polarization component magnitude to the minimum polarization component magnitude. The maximum polarization component at a pixel can be simply approximated by the brightest of the 0^o, 45^o, and 90^o component orientations, and the minimum polarization component the least bright value with respect to these orientations. The division of the magnitude of the maximum polarization component by the magnitude of the minimum polarization component will be termed the *polarization ratio.* The presence of a high polarization ratio will clearly produce a dominant light-dark "scintillating" psychophysical effect.

In storage tanks there are different degrees and different types of rusting. In a previous study in June 1994 sponsored by Lt. Michael Roer of the Environmental Safety Branch of the U.S. Coast Guard, a polarization camera sensor was successfully used to detect rusting on painted ship hulls underwater (as well as exposed metal from scrape damage) using linear polarized illumination- linear polarized light reflected off of rust has a significantly higher polarization ratio than linearly polarized light reflected off of painted ship hulls underwater. This is because rust has more specular reflection than does paint. Unfortunately due to moisture content in the storage tank on the U.S.S. Milwaukee, condensed water vapor even

on an unrusted painted surfaces produced a significantly high polarization ratio as compared with the rust itself which made it hard to differentiate rusted from unrusted portions of the painted walled surface. The explanation is that linearly polarized light from air reflected off of water droplets is still nearly linearly polarized which has a high polarization ratio-water droplets coating a painted surface produce much more specular reflection than from a dry surface. For this reason the inspectors found the Polarization Goggles distracting because almost every part of the interior of the storage tank was "scintilating" at once (as opposed to underwater operation where rust and scrapes are perceived to "scintillate" far more dominantly than undamaged portions). Unfortunately we did not get a chance to examine exposed unrusted metal damage as there was no such damage of this type present.

While psychophysically the use of polarization was found to be a bit distracting, automated computational processing of polarization ratios from the recorded video tape footage proved to be potentially very useful in significantly augmenting the capability of a video camera assessing damage to a ship storage tank. There are quantitative effects of the "scintillation" that are not apparent to human vision but that can be extracted using computational processing. In particular, the thresholding of high and low polarization ratios proved to be very useful in identifying where rusting produces cracking giving a good indicator as to how much rust is actually present, as well as how far rust protrudes from the storage tank wall. In addition cracking and protrusions due to rusting can be more easily distinguished from protrusions produced by undamaged portions of the storage tank such as from protruding beams.

The following figures of images taken inside the storage tank on the U.S.S. Milwaukee directly compare intensity image data as seen with a standard intensity view (the "a" suffix), with augmentation of information provided by polarization (the "b" suffix).

Figure 1a shows an intensity view of a dark region on a vertical wall of the storage tank. It may not be apparrent whether the dark region is due to shadowing caused by a large gouge in the wall, or, whether it could be simply black rust. Figure 1b shows the superimposed color label yellow to represent where the polarization ratio is above 5.0, revealing a distinctive signature of black rust, as opposed to shadowing caused by a gouge (which would produce a polarization ratio very close to 1.0- the lowest possible value). This signature is certainly not apparent in a conventional intensity view.

Figures 2a and 2b show what happens for a gouge in a thick layer of rust that has accumulated on one of the vertical walls of the storage tank. From the intensity image of Figure 2a it may be hard to tell whether the dark region is black rust or shadowing from a gouge or crack. Shadowing produces a very small polarization ratio between 1.0 and 1.1, and the red superimposed color label represents where this range of polarization ratio is present in the image. The yellow superimposed color label is as before, showing where the polarization ratio is above 5.0. Cracks and gouges not only show a low (i.e., red) polarization ratio where

shadowing occurs, but a high (i.e., yellow) polarization ratio where a protruding edge of the crack or gouge occurs, adjacent to the shadow. This same type of polarization signature is also apparent in Figures 3a and 3b where cracking from rust chipping off a vertical wall is shown. Figures 4a and 4b shows a head-on view of a mass of rust that has accumulated on another vertical wall- is this surrounded by black rust or by shadow ? In fact in Figure 4b the rust is protruding from the wall as can be ascertained by the red indicating the presence of shadow, and very thin edge protrusions with high polarization ratio in yellow. In Figure 4b the edge protrusions can be seen to be very thin and not evenly consistent because the rust protrusion is not caused by a cracking effect but rather a "caking up" effect on the side of the storage tank wall. This shows how polarization information can give augmented insight into the structural characteristics of rusting.

Figures 5a and 5b show in comparison shadows cast by protruding structural supports inside the storage tank, as opposed to shadows that are cast by cracking and gouging- note the same low polarization ratio signature (i.e., red) but that there is no accompanying band of high polarization ratio (i.e., yellow) from an accompanying protruding edge.

Figures 6a and 6b shows rust on the ceiling of the storage tank. Yellow color label once again representing a polarization ratio above 5.0 depicts where parts of the rust protrude away from the ceiling indicating where larger rust deposits are present.

What was coincidentally noticed using the polarization goggles was how they made it easier for a human viewer to identify oil floating on the top of the water surface in the Philadelphia Naval Yard Harbor. We were not allowed to use photographing equipment outside the ship so we were not able to record quantitative data on this.

RECOMMENDATIONS

This study has shown that polarization information has a good potential for augmenting sensory information obtained by a video camera that is being used to inspect damage in a storage tank (e.g., a video camera installed on a magnetic crawler can be easily modified using light weight equipment to include polarization information and enhance). However this is at the automated level where a technician level operator can analyze the polarization imagery.

It appears that polarization goggles are not directly useful to inspectors inside storage tanks. but from the previous underwater study at the Naval Surface Warfare Center, Annapolis. Maryland, they may be very useful to underwater divers inspecting ship hull damage.

It was perhaps unfortunate that we were not able to look at a storage tank that was considered by the inspectors to be "significantly damaged". More capabilities for polarization vision may be revealed by inspection of a more damaged storage tank.

Last but not least the accidental discovery of the use of polarization vision to more accurately detect oil slicks should probably be investigated further.

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FIGURE 1a

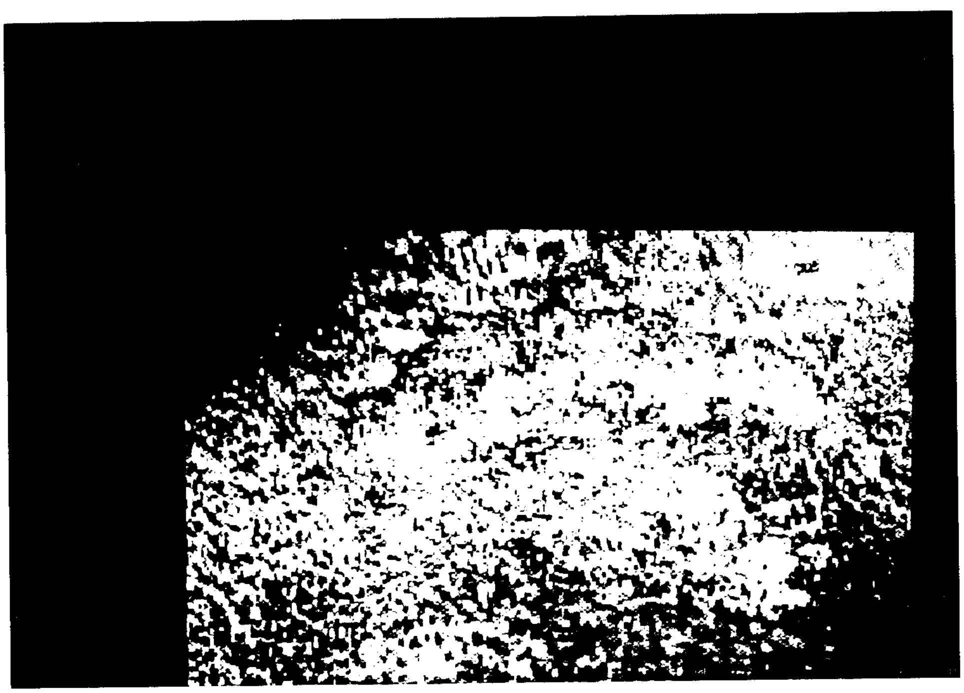

FIGURE 1b

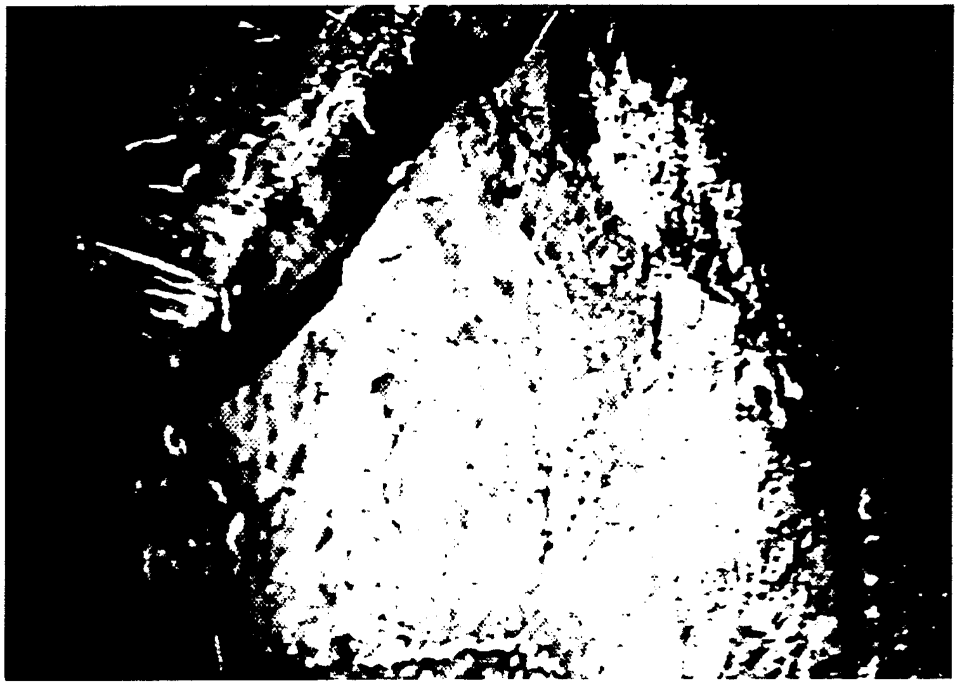

FIGURE 2a

FIGURE 2b

FIGURE 3a

FIGURE 3b

FIGURE 4a

FIGURE 4b

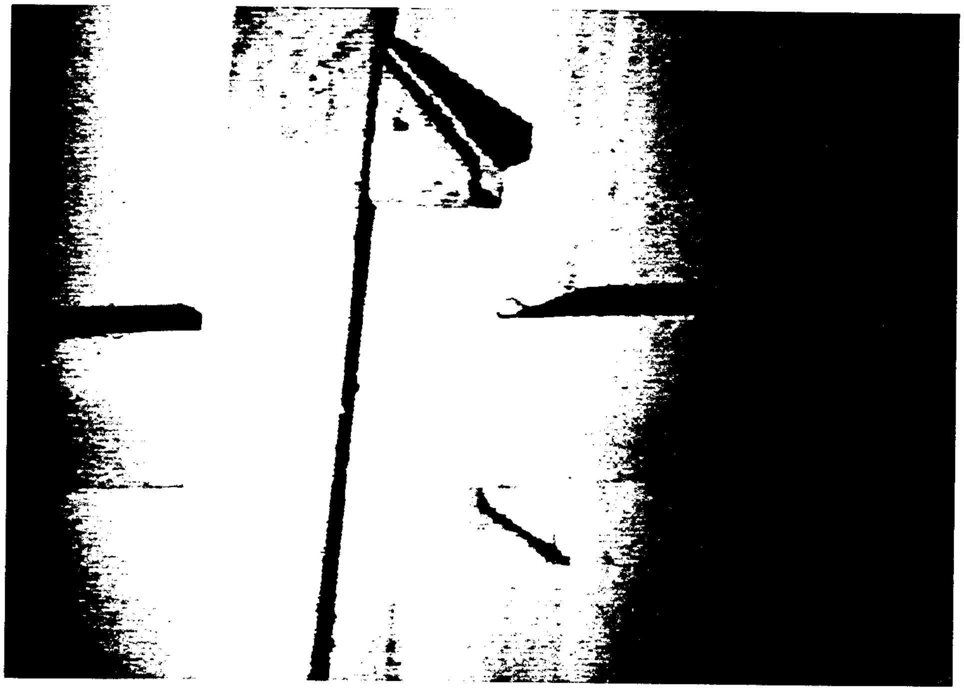

FIGURE 5a

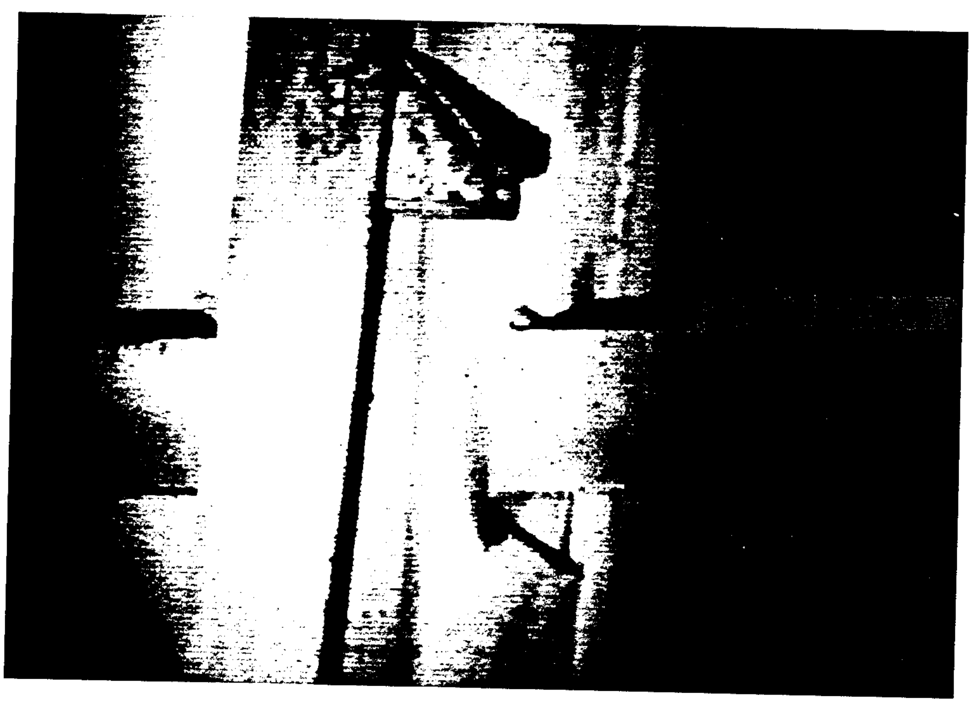

FIGURE 5b

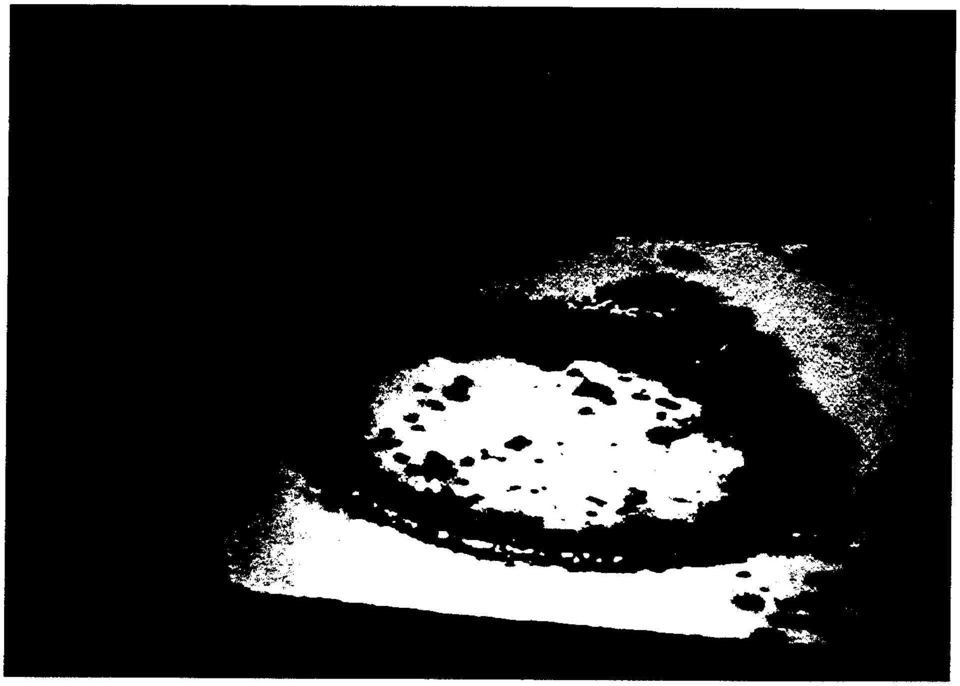

FIGURE 6a

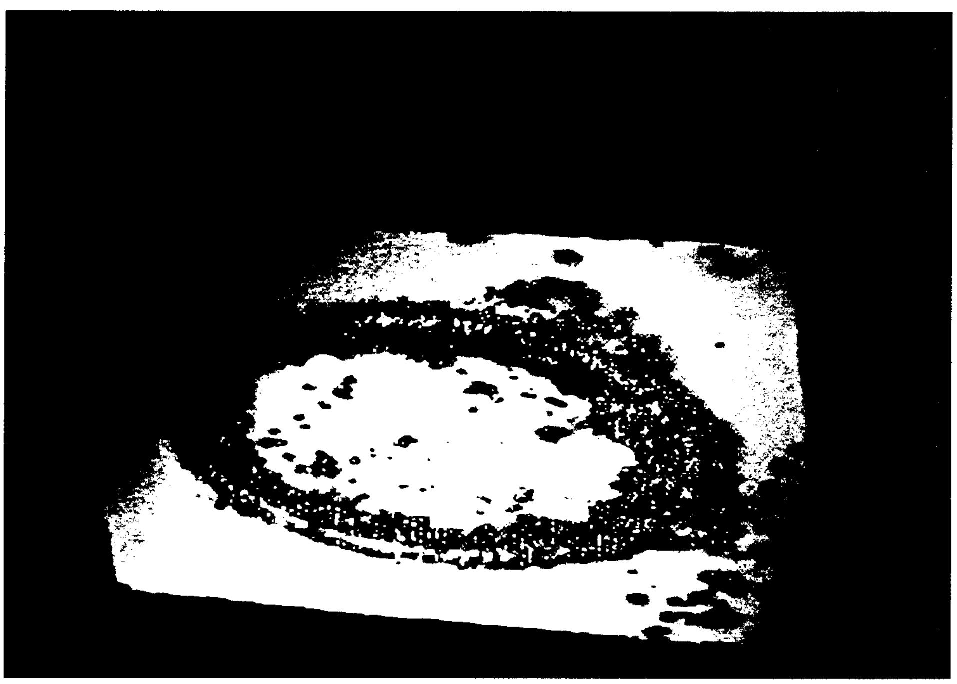

FIGURE 6b